US011787688B2

(12) **United States Patent**
Lee et al.

(10) **Patent No.: US 11,787,688 B2**
(45) **Date of Patent: Oct. 17, 2023**

(54) **METHODS OF FORMING MEMS DIAPHRAGMS INCLUDING CORRUGATIONS**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 163 days.

(21) Appl. No.: **17/099,442**

(22) Filed: **Nov. 16, 2020**

(65) **Prior Publication Data**

US 2021/0070610 A1 Mar. 11, 2021

Related U.S. Application Data

(63) Continuation of application No. 16/593,498, filed on Oct. 4, 2019, now Pat. No. 10,870,577.

(Continued)

(51) **Int. Cl.**

B81C 1/00	(2006.01)
B81B 3/00	(2006.01)

(Continued)

(52) **U.S. Cl.**
CPC ***B81C 1/00158*** (2013.01); ***B81B 3/0021*** (2013.01); ***G01L 9/0042*** (2013.01);
(Continued)

(58) **Field of Classification Search**
CPC .. H04R 19/04; H04R 7/04; H04R 7/18; B81C 1/00158; B81B 3/0021; B81B 2203/0127; B81B 2201/0257
See application file for complete search history.

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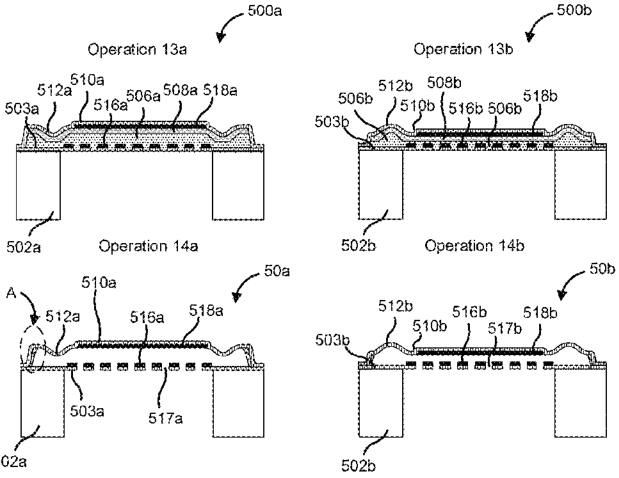
Primary Examiner — Jaehwan Oh
Assistant Examiner — John M Parker
(74) *Attorney, Agent, or Firm* — FOLEY & LARDNER LLP

(57) **ABSTRACT**

A method of forming an acoustic transducer comprises providing a substrate and depositing a first structural layer on the substrate. The first structural layer is selectively etched to form at least one of an enclosed trench or an enclosed pillar thereon. A second structural layer is deposited on the first structural layer and includes a depression or a bump corresponding to the enclosed trench or pillar, respectively. At least the second structural layer is heated to a temperature above a glass transition temperature of the second structural layer causing the second structural layer to

(Continued)



reflow. A diaphragm layer is deposited on the second structural layer such that the diaphragm layer includes at least one of a downward facing corrugation corresponding to the depression or an upward facing corrugation corresponding to the bump. The diaphragm layer is released, thereby forming a diaphragm suspended over the substrate.

15 Claims, 30 Drawing Sheets

Related U.S. Application Data

(60) Provisional application No. 62/742,164, filed on Oct. 5, 2018.

(51) **Int. Cl.**

H04R 31/00	(2006.01)
G01L 9/00	(2006.01)

(52) **U.S. Cl.**

CPC ***H04R 31/003*** (2013.01); *B81B 2201/0257* (2013.01); *B81B 2201/0264* (2013.01); *B81B 2203/0127* (2013.01); *B81C 2201/0132* (2013.01); *B81C 2201/0133* (2013.01)

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FIG. 1A

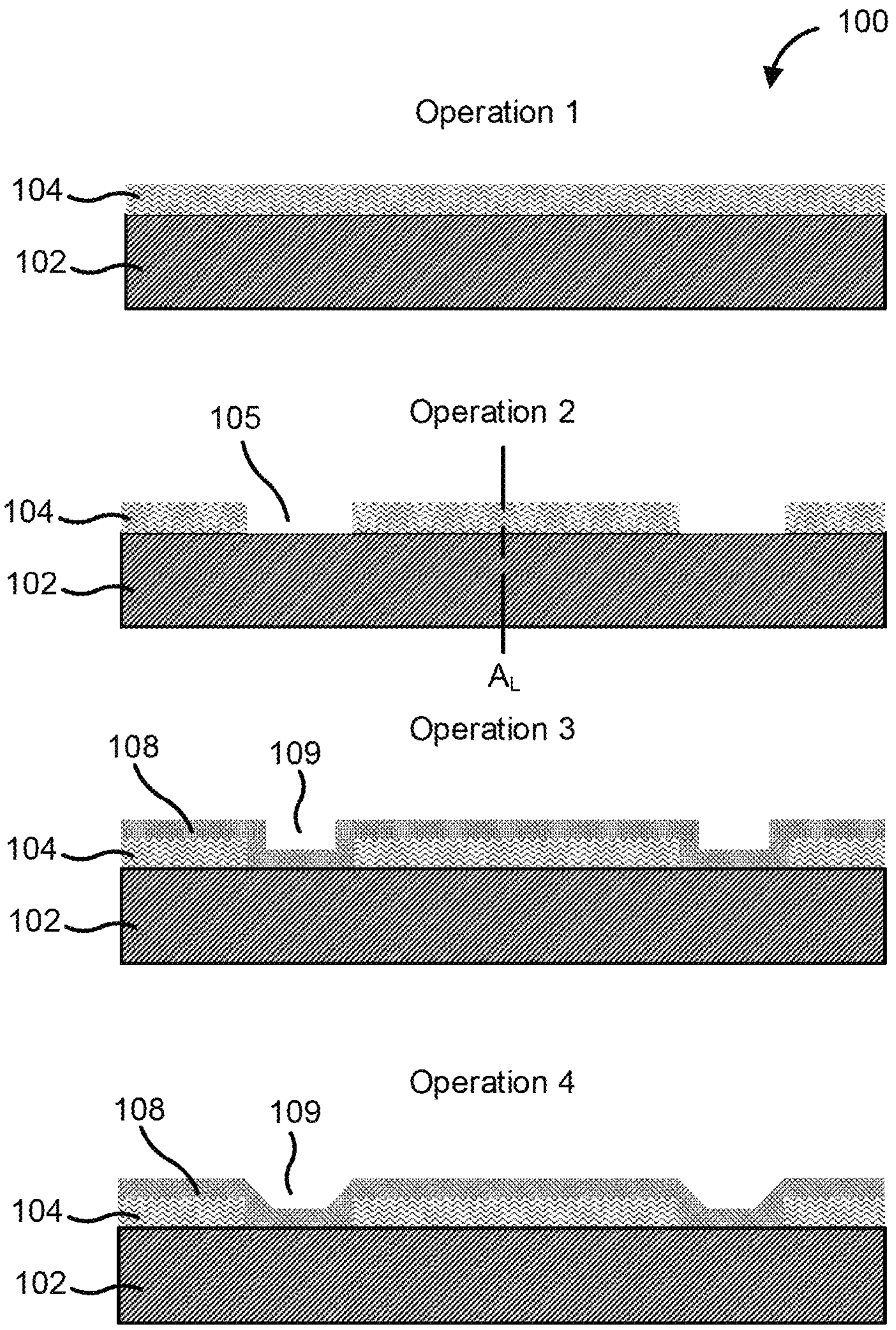
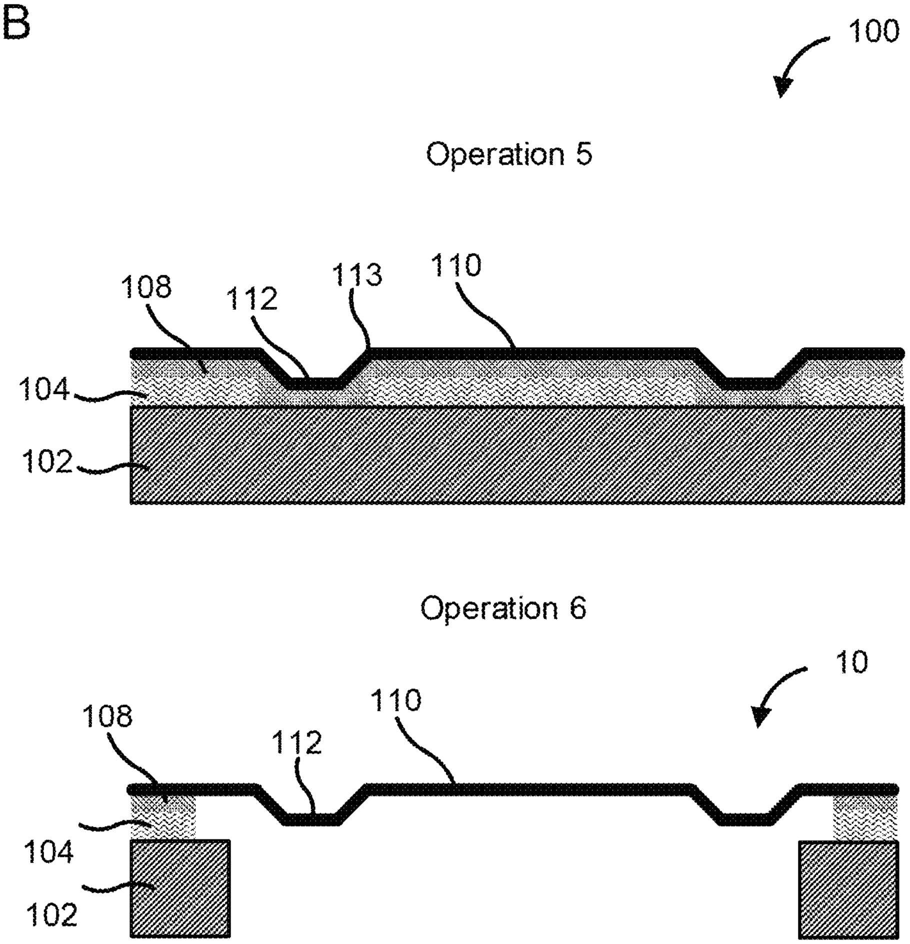

100
Operation 1
104
102
105
Operation 2
104
102
A_L
Operation 3
108
109
104
102
Operation 4
108
109
104
102

FIG. 1B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113
110
104
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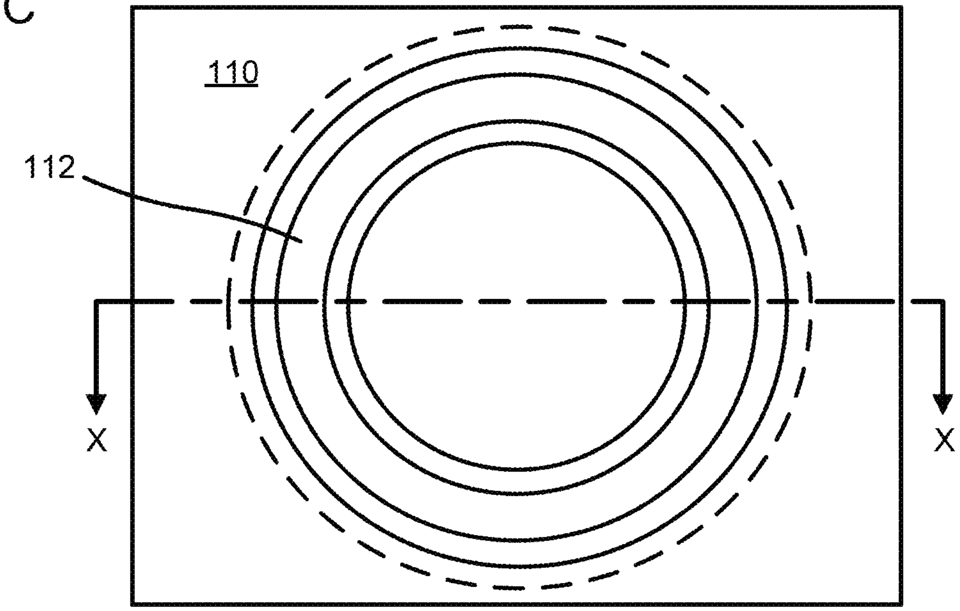
Operation 6
10
108
110
112
104
102

FIG. 1C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112
X
X

FIG. 2A

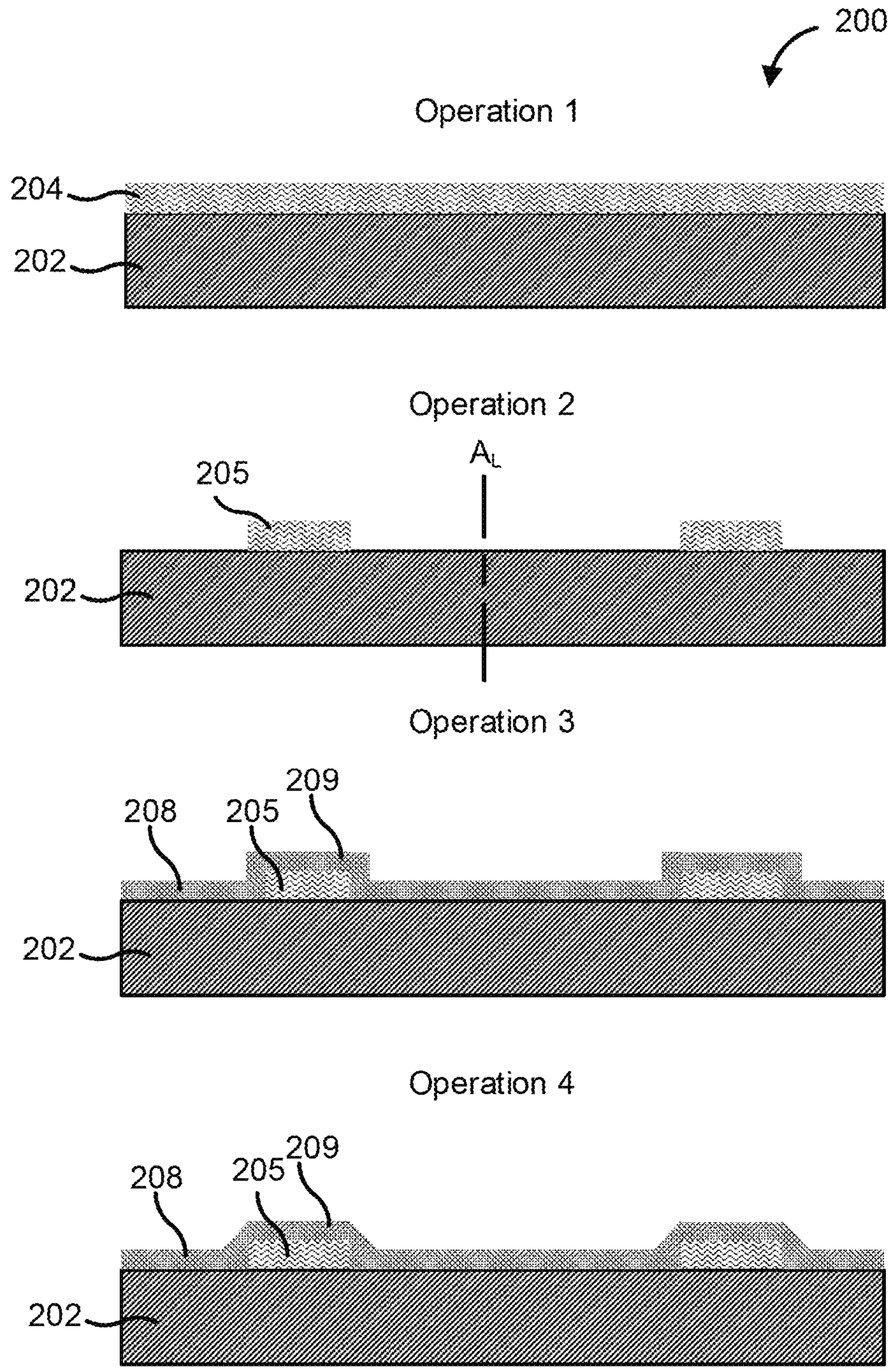

200
Operation 1
204
202
Operation 2
205
A_L
202
Operation 3
209
208
205
202
Operation 4
209
208
205
202

FIG. 2B

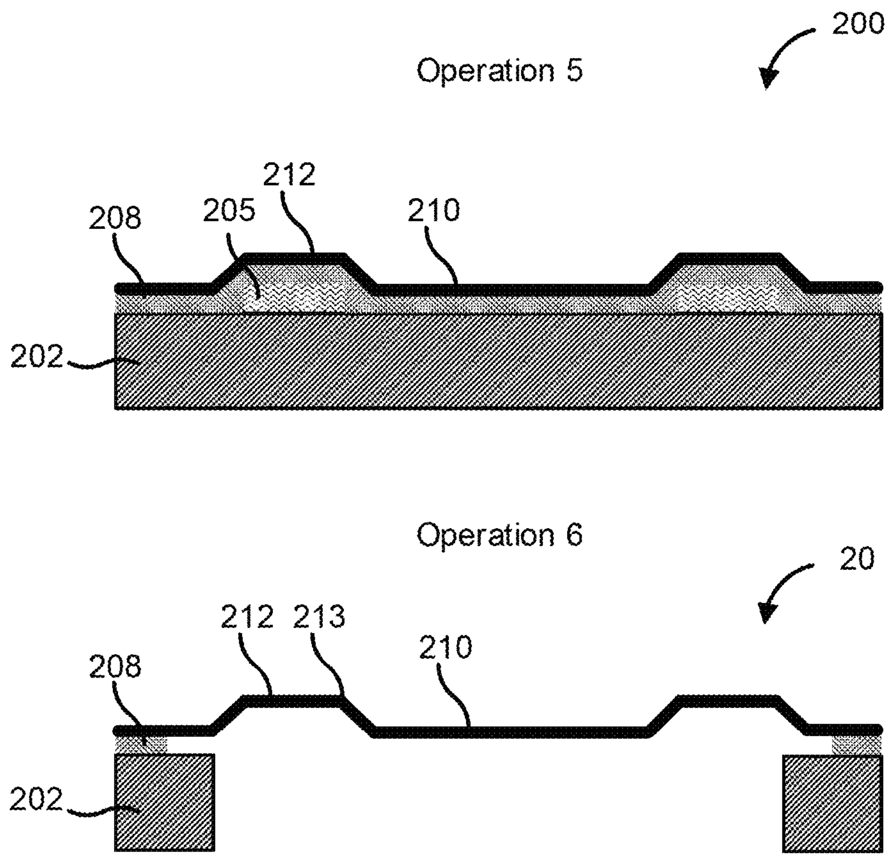

Operation 5
200
212
208
205
210
202
Operation 6
20
212
213
208
210
202

FIG. 2C

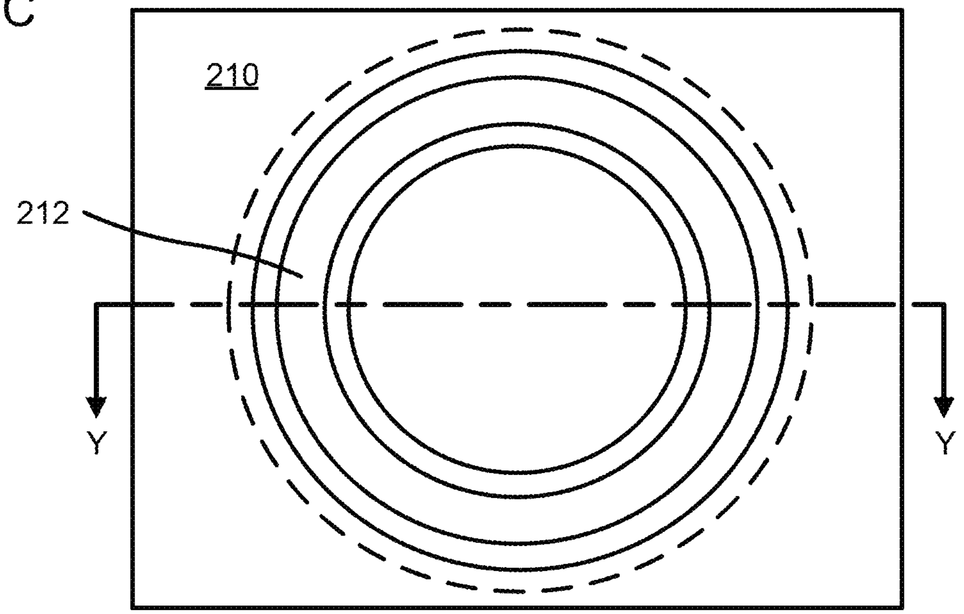

210
212
Y
Y

FIG. 3

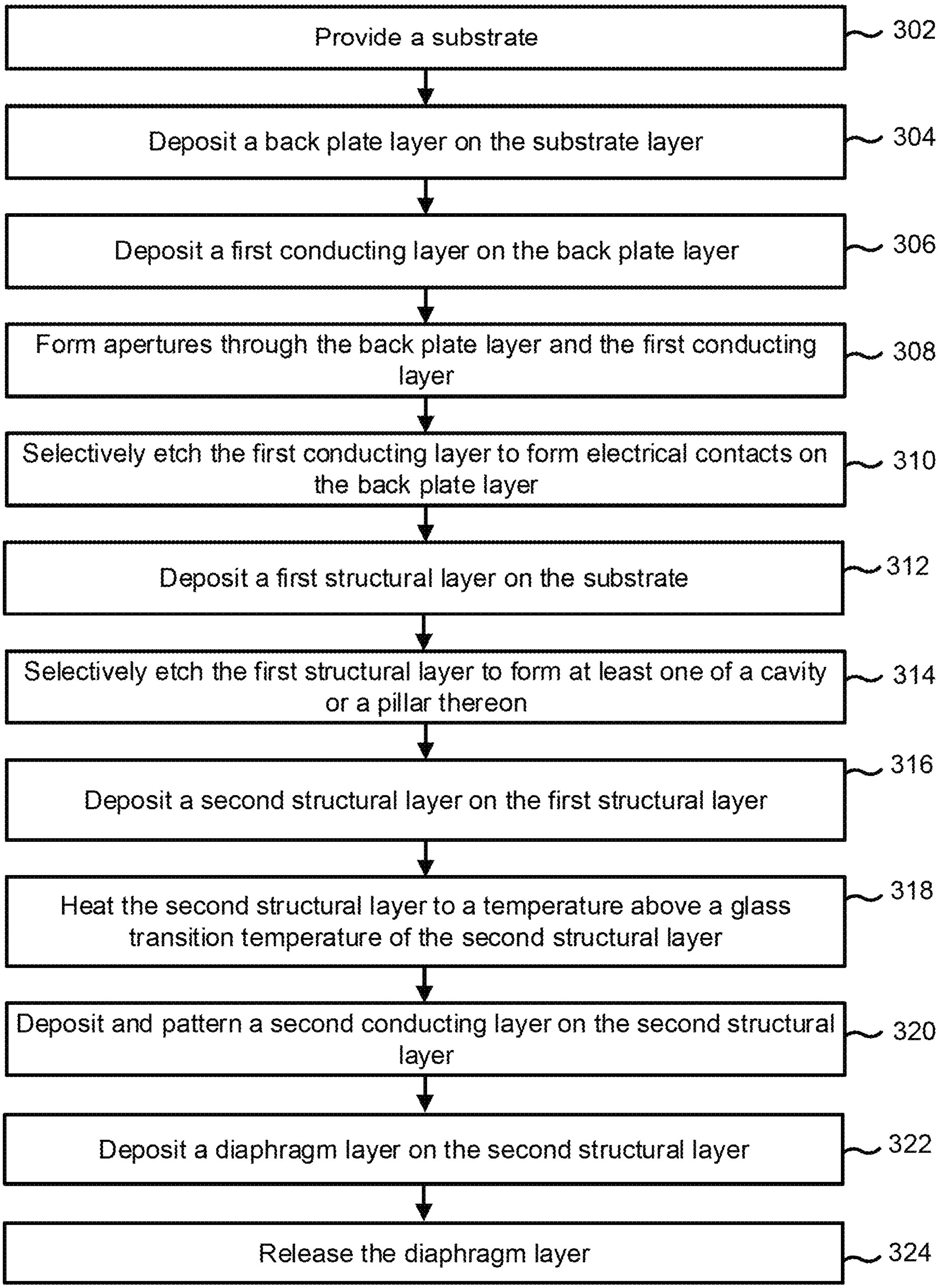

300
Provide a substrate
302
Deposit a back plate layer on the substrate layer
304
Deposit a first conducting layer on the back plate layer
306
Form apertures through the back plate layer and the first conducting layer
308
Selectively etch the first conducting layer to form electrical contacts on the back plate layer
310
Deposit a first structural layer on the substrate
312
Selectively etch the first structural layer to form at least one of a cavity or a pillar thereon
314
Deposit a second structural layer on the first structural layer
316
Heat the second structural layer to a temperature above a glass transition temperature of the second structural layer
318
Deposit and pattern a second conducting layer on the second structural layer
320
Deposit a diaphragm layer on the second structural layer
322
Release the diaphragm layer
324

FIG. 4A

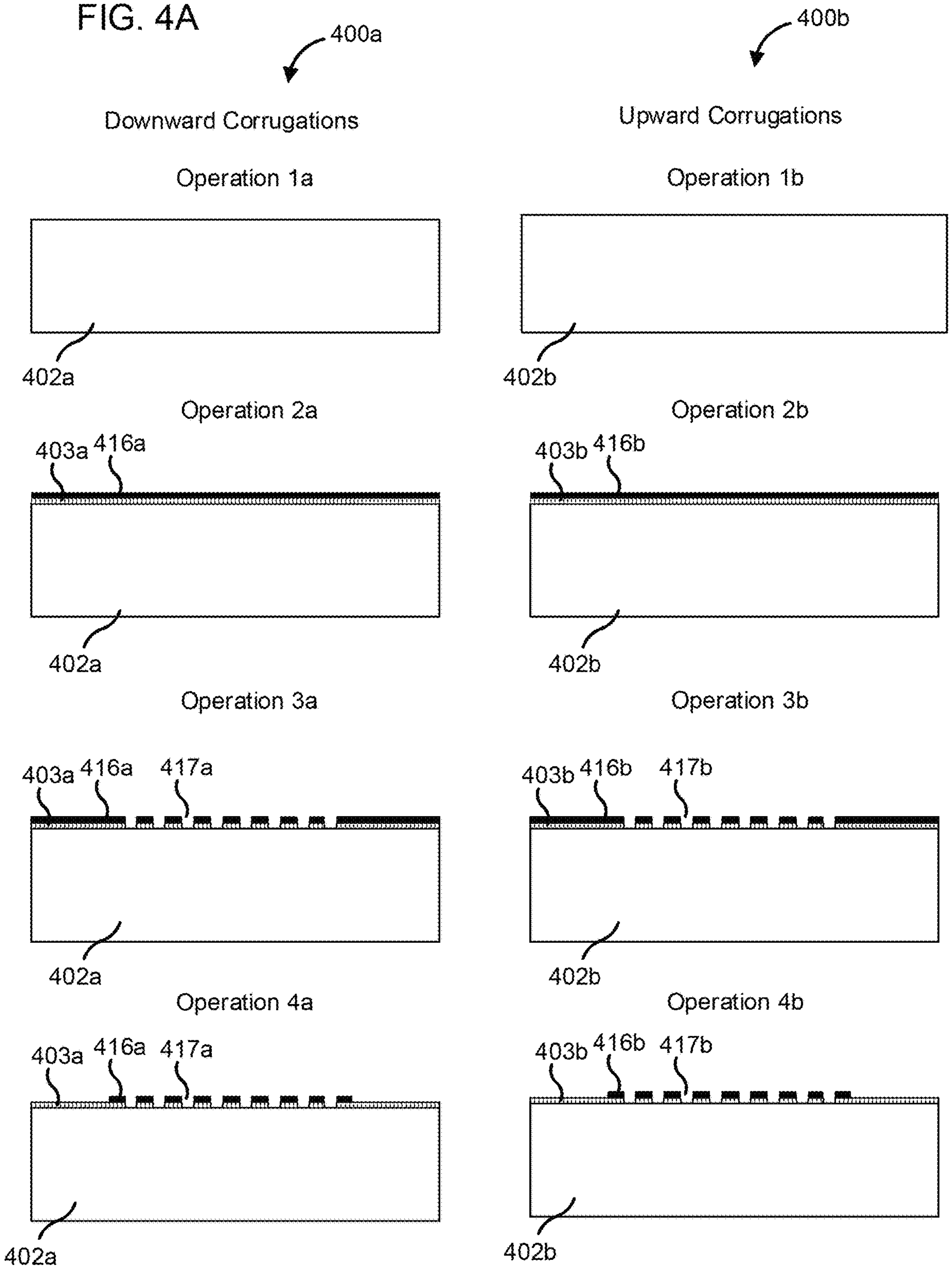
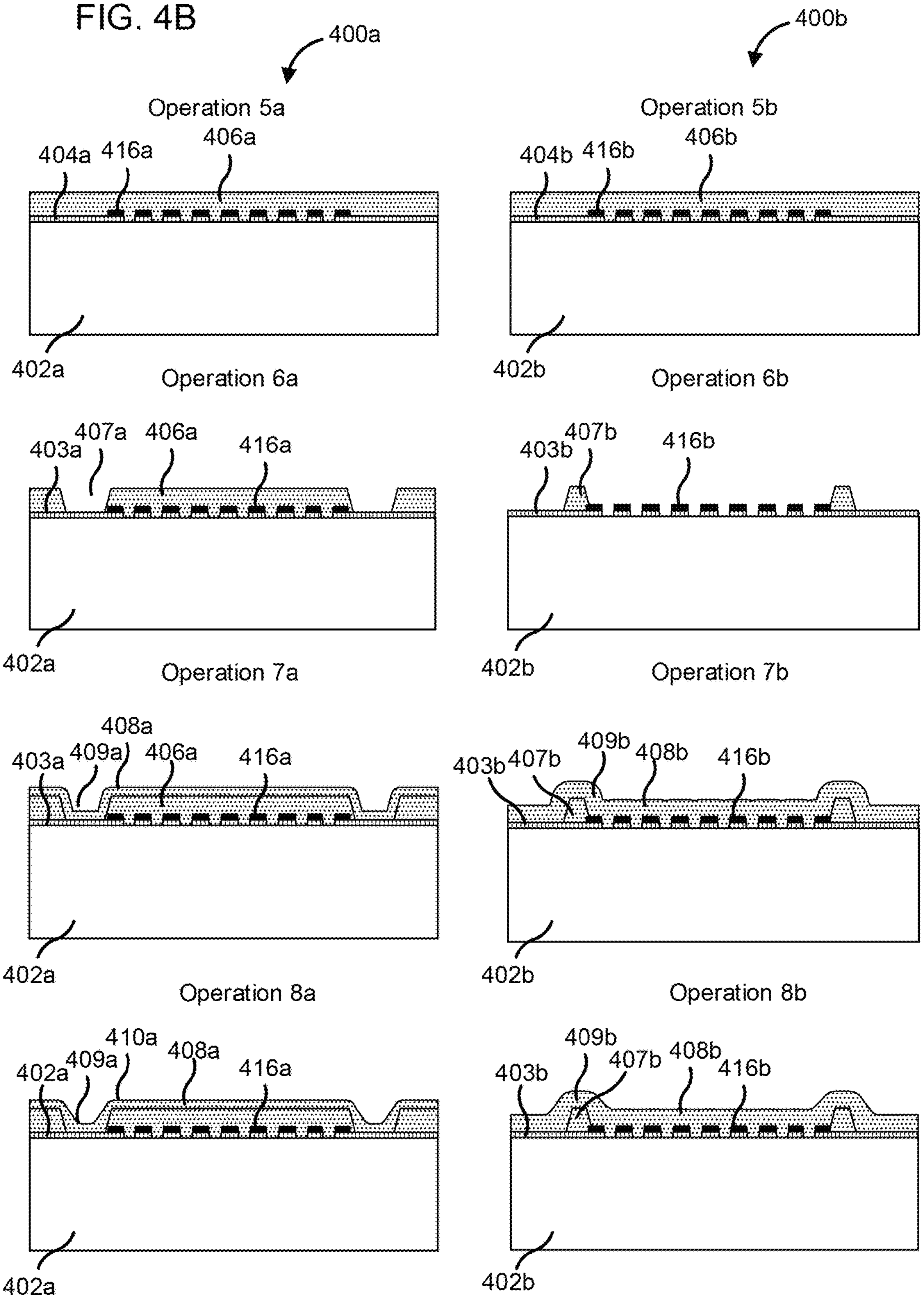

400a
400b
Downward Corrugations
Upward Corrugations
Operation 1a
Operation 1b
402a
402b
Operation 2a
Operation 2b
403a
416a
403b
416b
402a
402b
Operation 3a
Operation 3b
403a
416a
417a
403b
416b
417b
402a
402b
Operation 4a
Operation 4b
403a
416a
417a
403b
416b
417b
402a
402b

FIG. 4B


400a
400b
Operation 5a
404a
416a
406a
402a
Operation 5b
404b
416b
406b
402b
Operation 6a
403a
407a
406a
416a
402a
Operation 6b
403b
407b
416b
402b
Operation 7a
408a
403a
409a
406a
416a
402a
Operation 7b
403b
407b
409b
408b
416b
402b
Operation 8a
410a
402a
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408a
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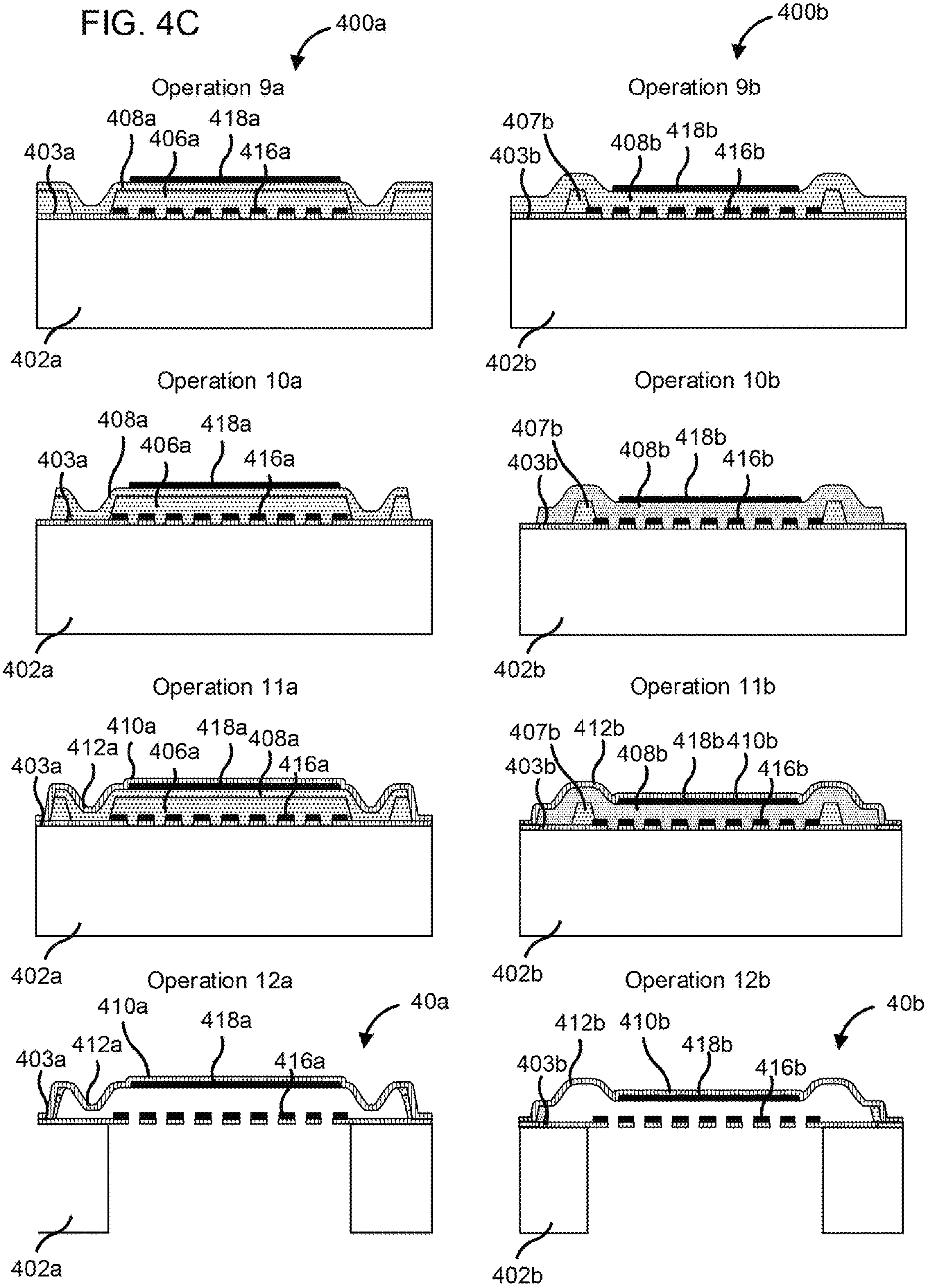
402a
Operation 8b
409b
403b
407b
408b
416b
402b

FIG. 4C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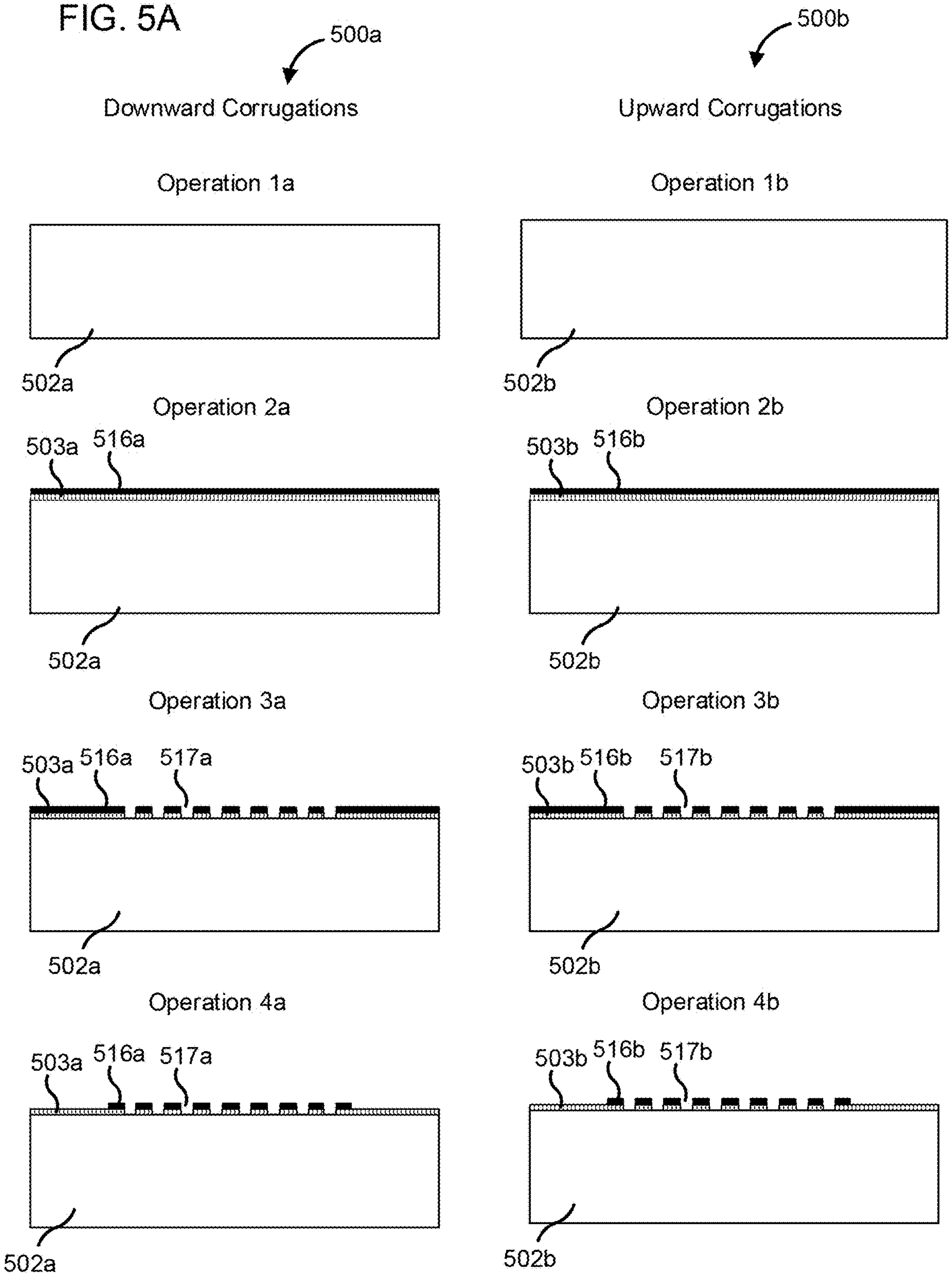
400b
Operation 9a
408a
418a
406a
403a
416a
402a
Operation 9b
407b
418b
408b
403b
416b
402b
Operation 10a
408a
418a
406a
403a
416a
402a
Operation 10b
407b
418b
408b
403b
416b
402b
Operation 11a
410a
418a
408a
412a
406a
403a
416a
402a
Operation 11b
407b
412b
418b
410b
408b
403b
416b
402b
Operation 12a
40a
410a
418a
412a
403a
416a
402a
Operation 12b
40b
412b
410b
418b
403b
416b
402b

FIG. 5A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500b
Upward Corrugations
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Operation 1b
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Operation 2a
503a
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502a
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516b
502b
Operation 3a
503a
516a
517a
502a
Operation 3b
503b
516b
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Operation 4a
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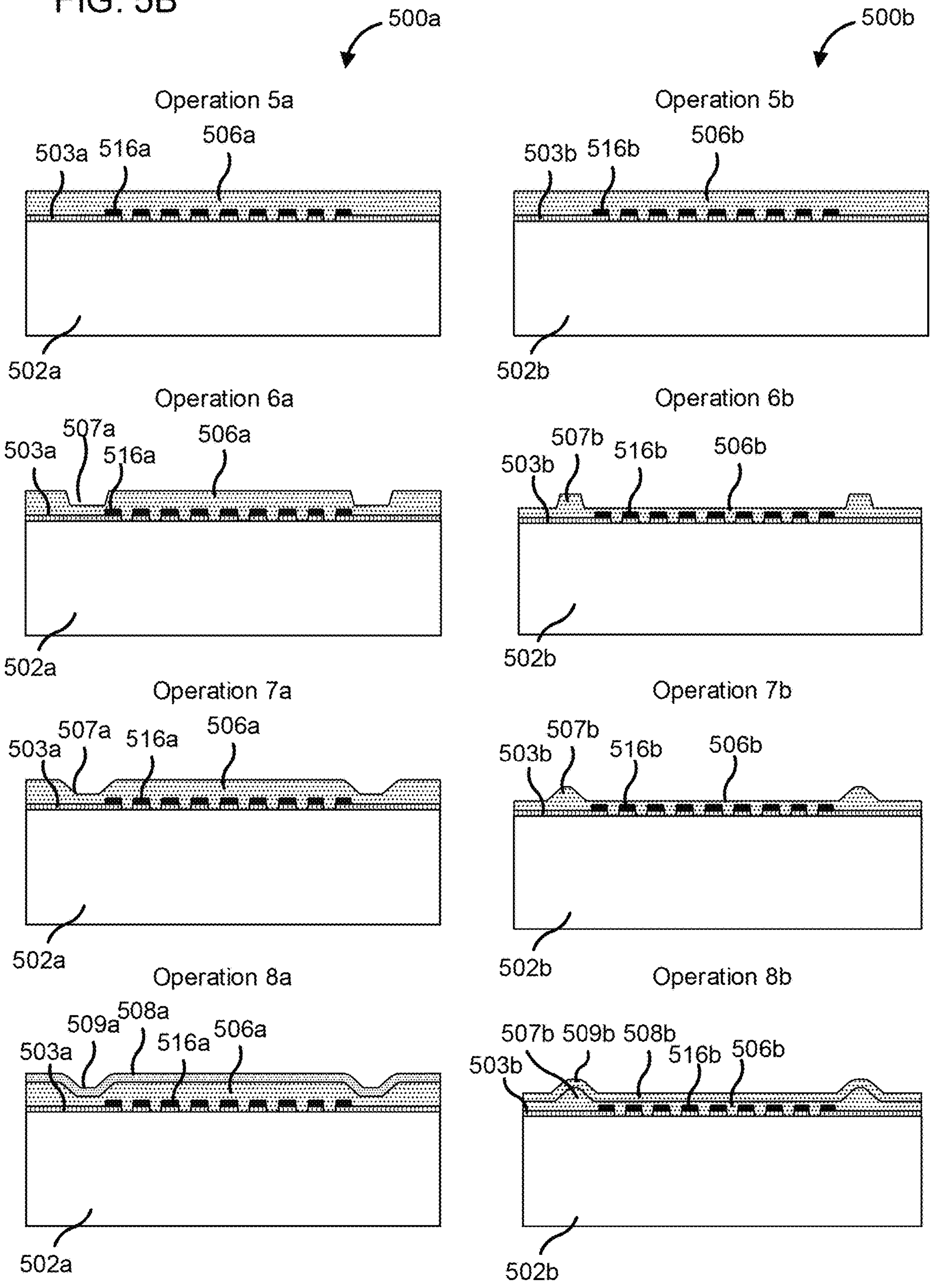
502a
Operation 4b
503b
516b
517b
502b

FIG. 5B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Operation 5a
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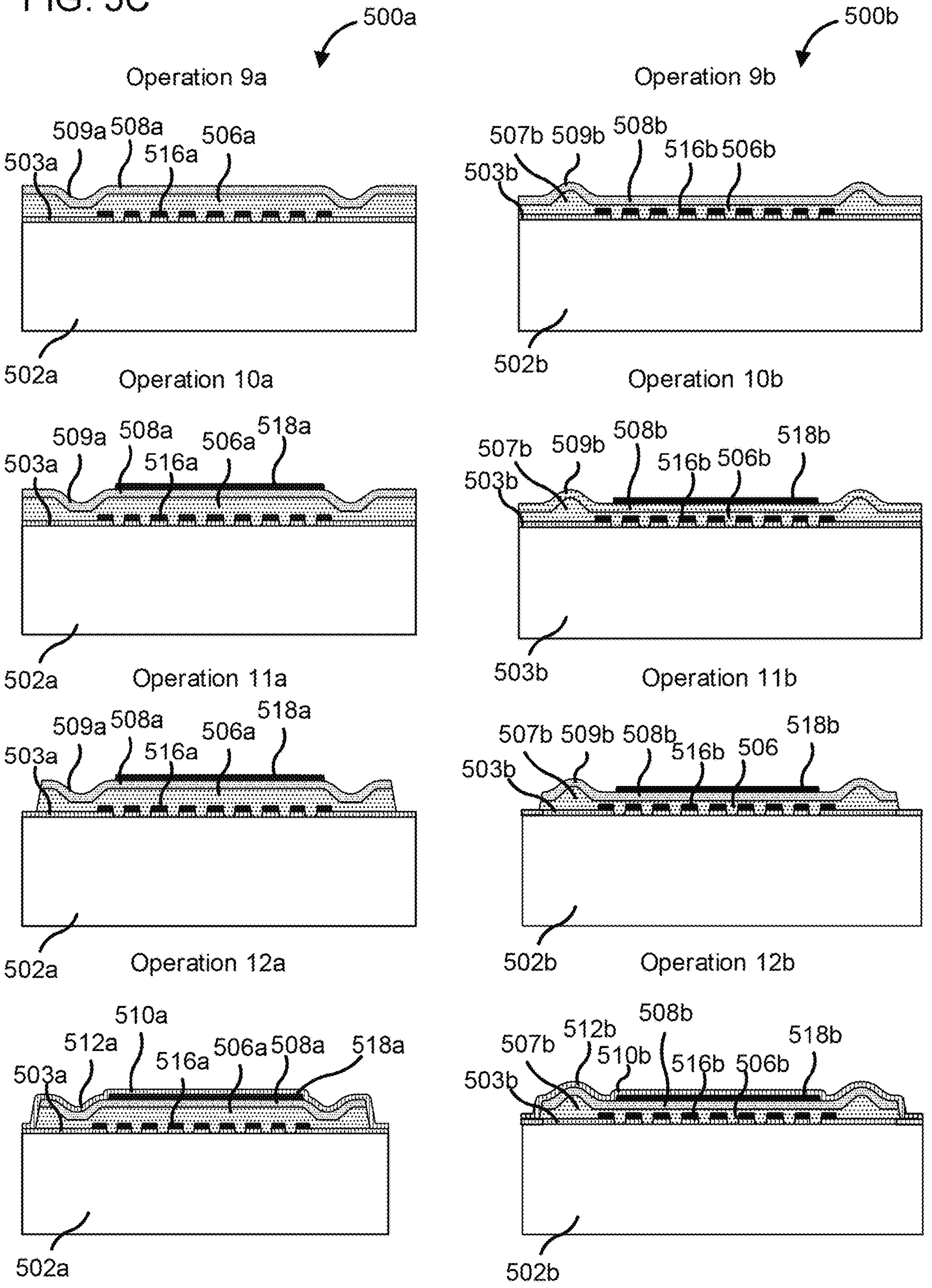
Operation 5b
503b
516b
506b
502b
Operation 6a
503a
507a
516a
506a
502a
Operation 6b
503b
507b
516b
506b
502b
Operation 7a
503a
507a
516a
506a
502a
Operation 7b
503b
507b
516b
506b
502b
Operation 8a
503a
509a
508a
516a
506a
502a
Operation 8b
503b
507b
509b
508b
516b
506b
502b

FIG. 5C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500b
Operation 9a
509a
508a
506a
503a
516a
502a
Operation 9b
507b
509b
508b
516b
506b
503b
502b
Operation 10a
509a
508a
506a
518a
503a
516a
502a
Operation 10b
507b
509b
508b
516b
506b
518b
503b
503b
Operation 11a
509a
508a
506a
518a
503a
516a
502a
Operation 11b
507b
509b
508b
516b
506
518b
503b
502b
Operation 12a
510a
512a
516a
506a
508a
518a
503a
502a
Operation 12b
507b
512b
510b
508b
516b
506b
518b
503b
502b

FIG. 5D

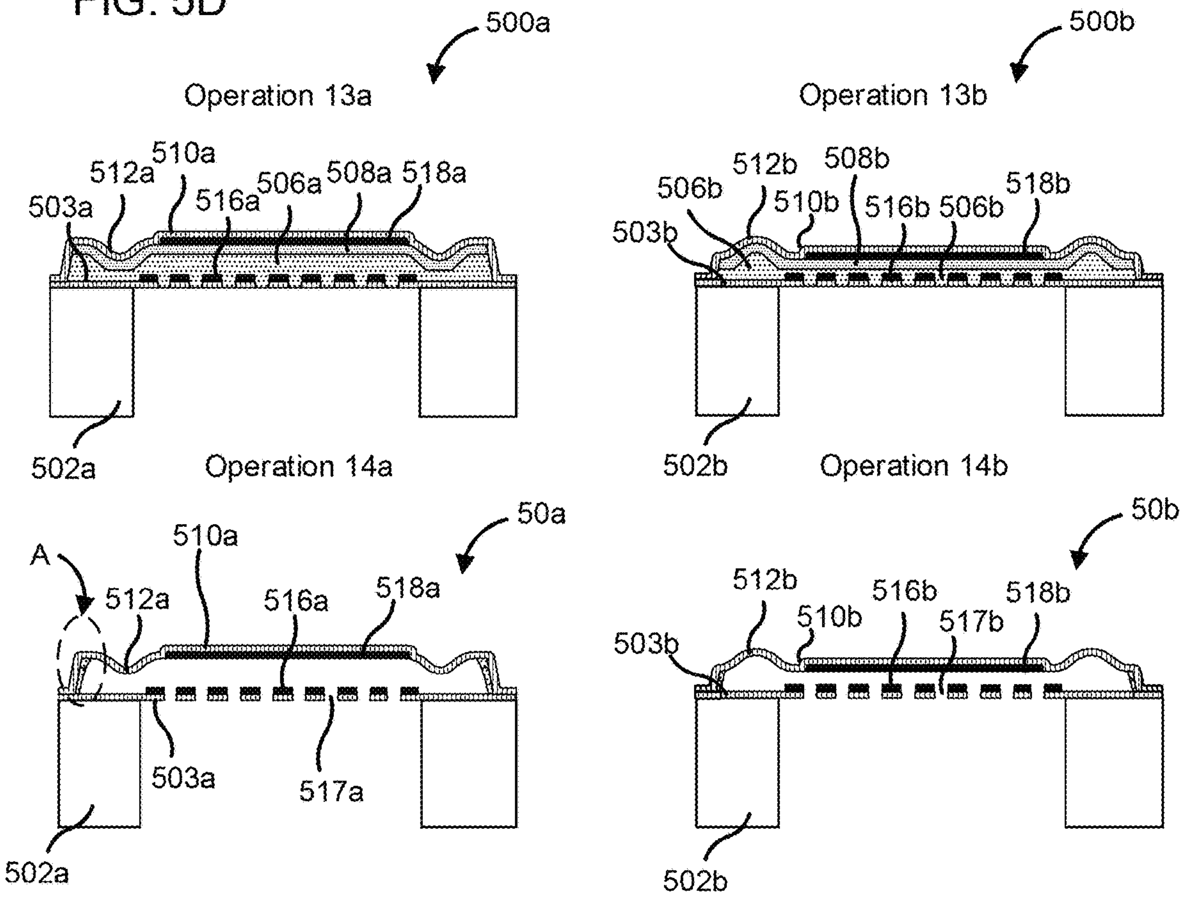

500a
Operation 13a
512a
510a
516a
506a
508a
518a
503a
502a
500b
Operation 13b
512b
508b
506b
510b
516b
506b
518b
503b
502b
Operation 14a
50a
A
510a
512a
516a
518a
503a
517a
502a
Operation 14b
50b
512b
516b
518b
510b
517b
503b
502b

FIG. 5E

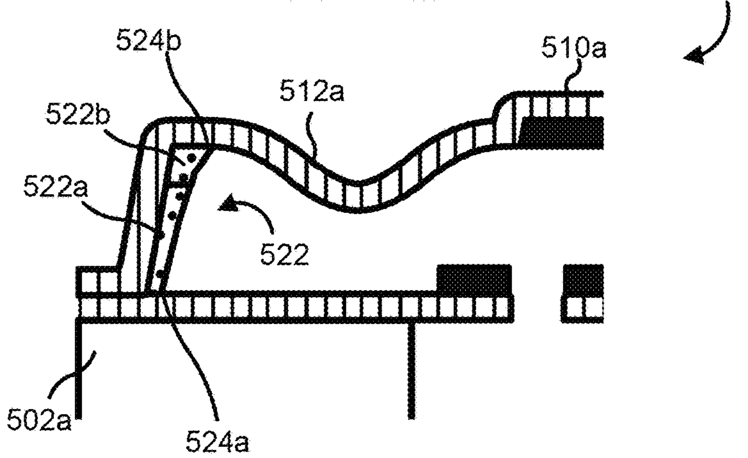

50a
524b
510a
512a
522b
522a
522
502a
524a

FIG. 6

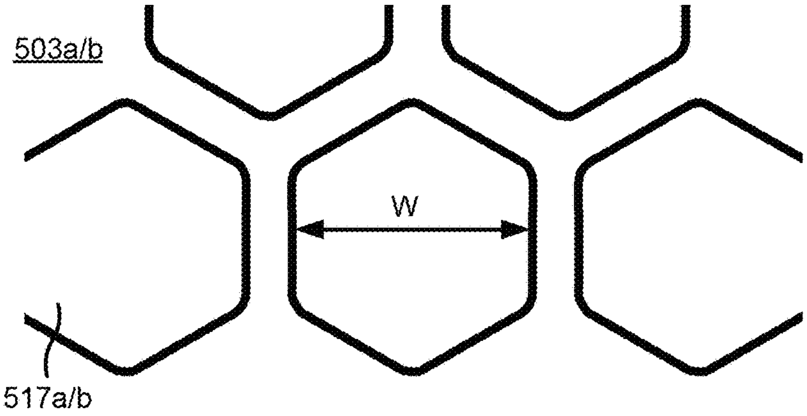


FIG. 7

A

Lot	Wafer	Corrugation Type/Etch	Smoothness	Failing Pressure (psi)
A	24	Down/Dry	Sharp	9
B	5	Down/Wet	Smooth	18
B	15	Down/Wet	Smooth	34
C	25	Down/Dry with PSG left	Smoothest	60

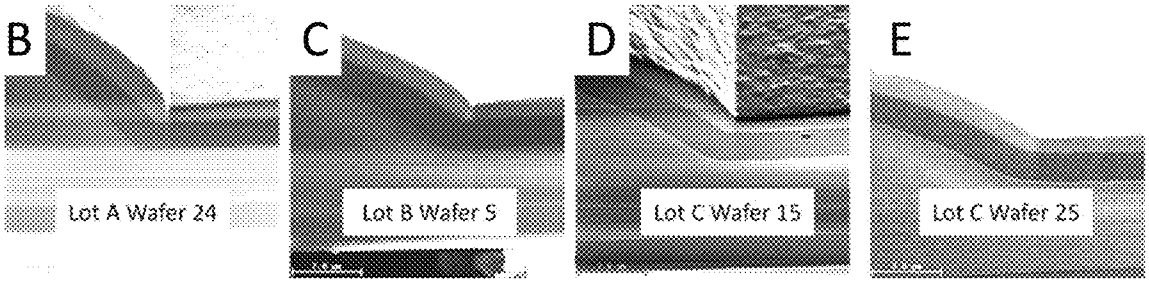


FIG. 8

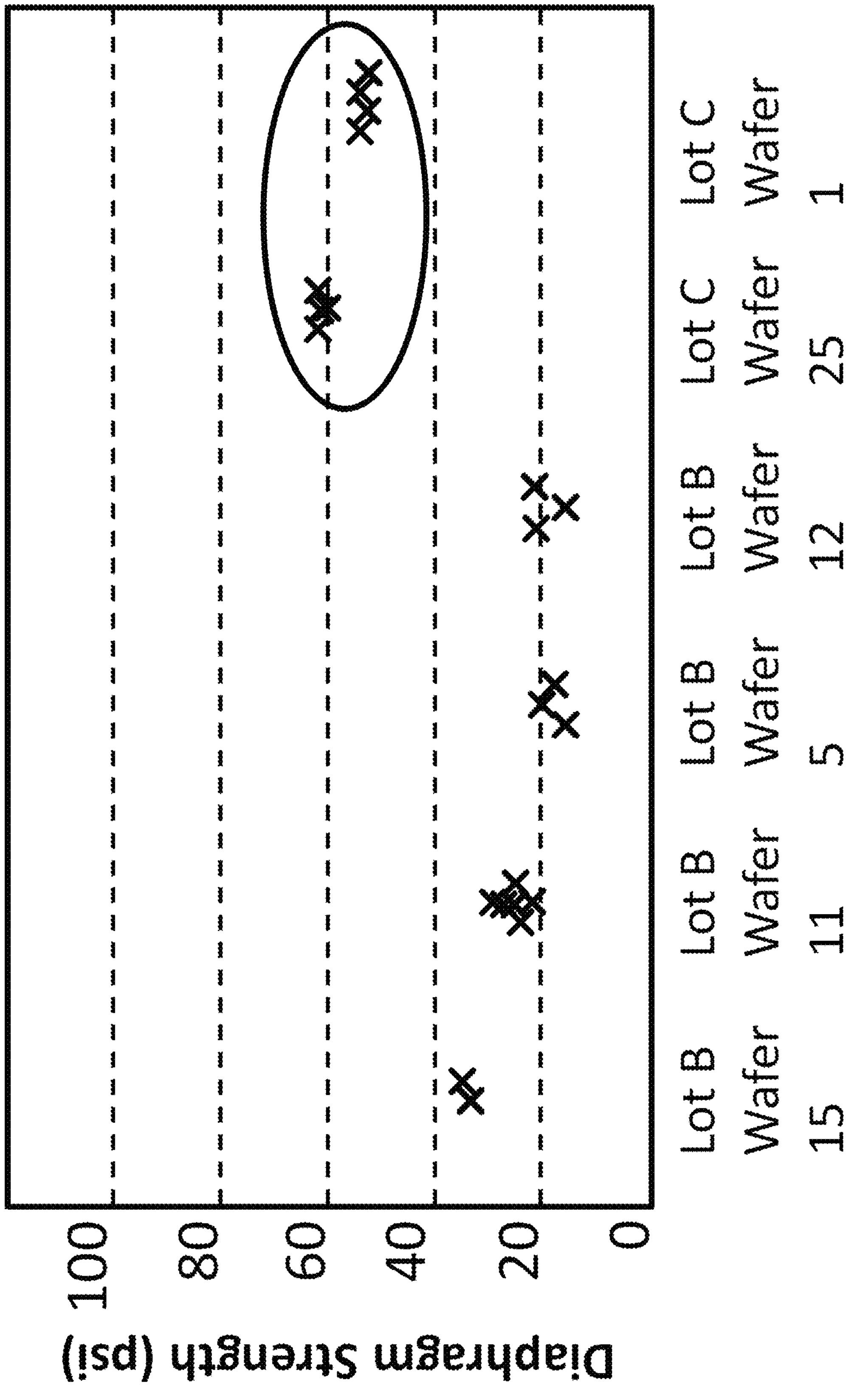

Diaphragm Strength (psi)
100
80
60
40
20
0
Lot B Wafer 15
Lot B Wafer 11
Lot B Wafer 5
Lot B Wafer 12
Lot C Wafer 25
Lot C Wafer 1

FIG. 9A

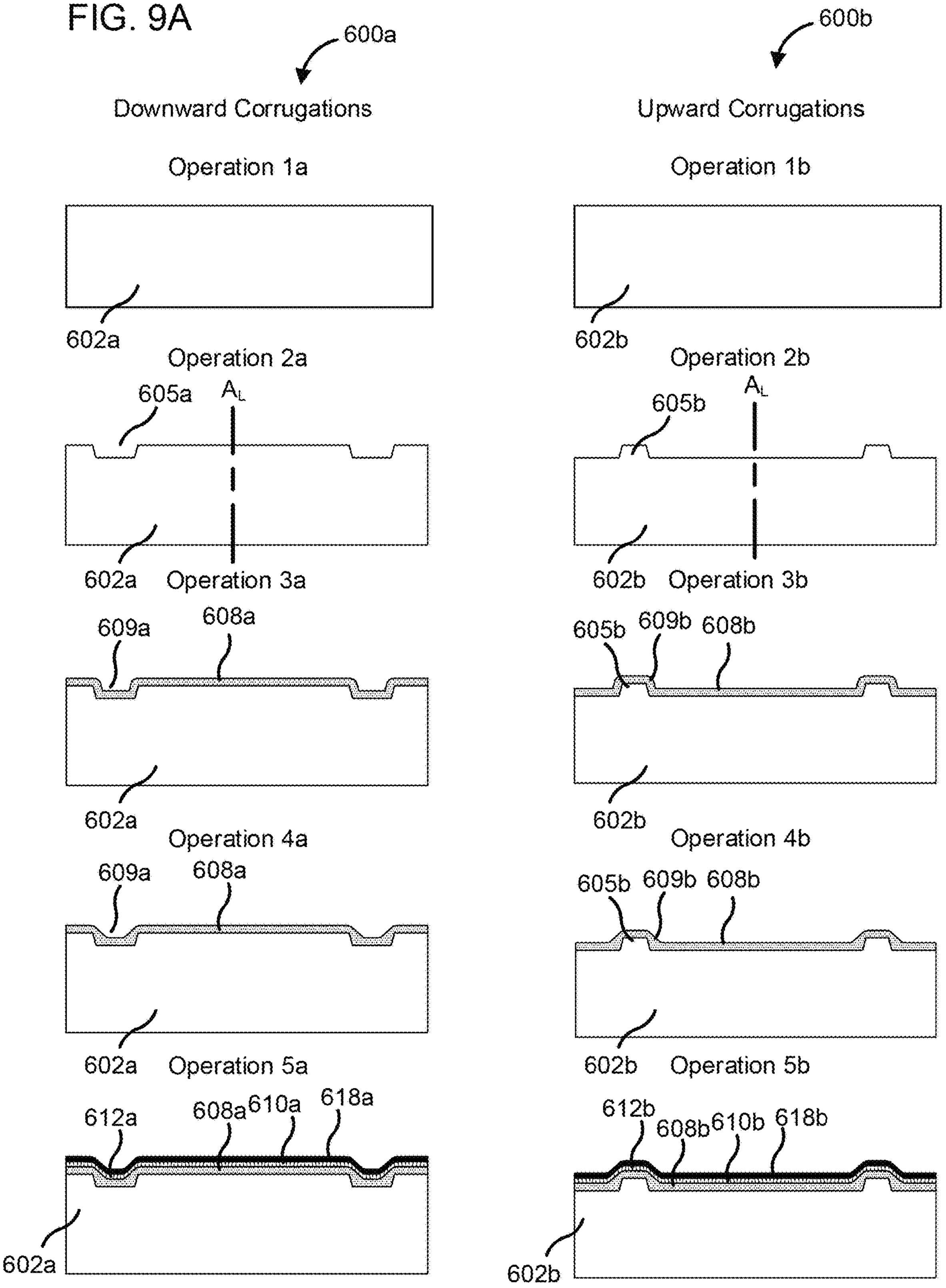

600a
Downward Corrugations
Operation 1a
602a
Operation 2a
605a
A_L
602a
Operation 3a
609a
608a
602a
Operation 4a
609a
608a
602a
Operation 5a
612a
608a
610a
618a
602a
600b
Upward Corrugations
Operation 1b
602b
Operation 2b
605b
A_L
602b
Operation 3b
605b
609b
608b
602b
Operation 4b
605b
609b
608b
602b
Operation 5b
612b
608b
610b
618b
602b

FIG. 9B

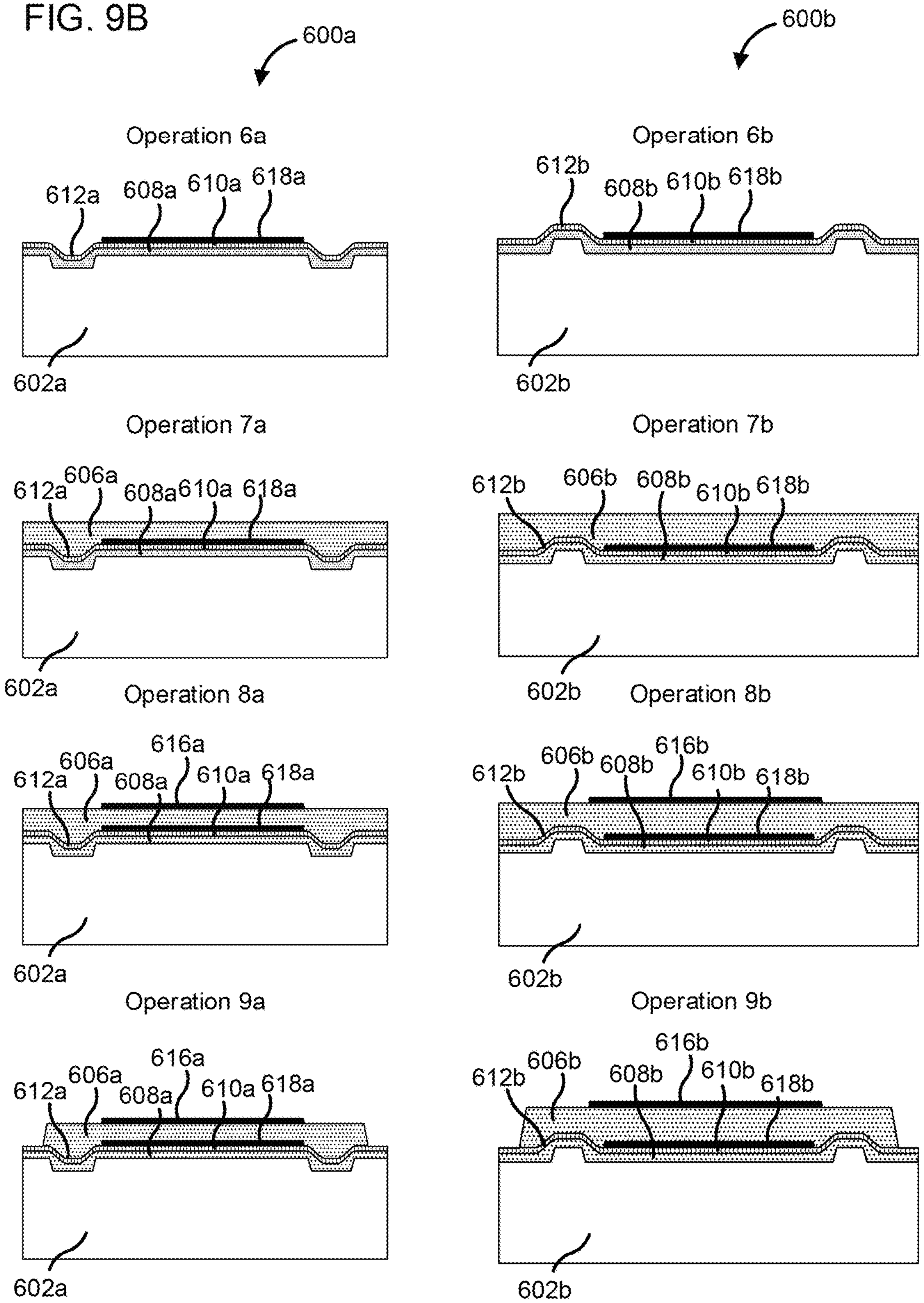

600a
600b
Operation 6a
612a
608a
610a
618a
602a
Operation 6b
612b
608b
610b
618b
602b
Operation 7a
612a
606a
608a
610a
618a
602a
Operation 7b
612b
606b
608b
610b
618b
602b
Operation 8a
616a
606a
612a
608a
610a
618a
602a
Operation 8b
616b
606b
608b
612b
610b
618b
602b
Operation 9a
616a
606a
612a
608a
610a
618a
602a
Operation 9b
616b
606b
612b
608b
610b
618b
602b

FIG. 9C

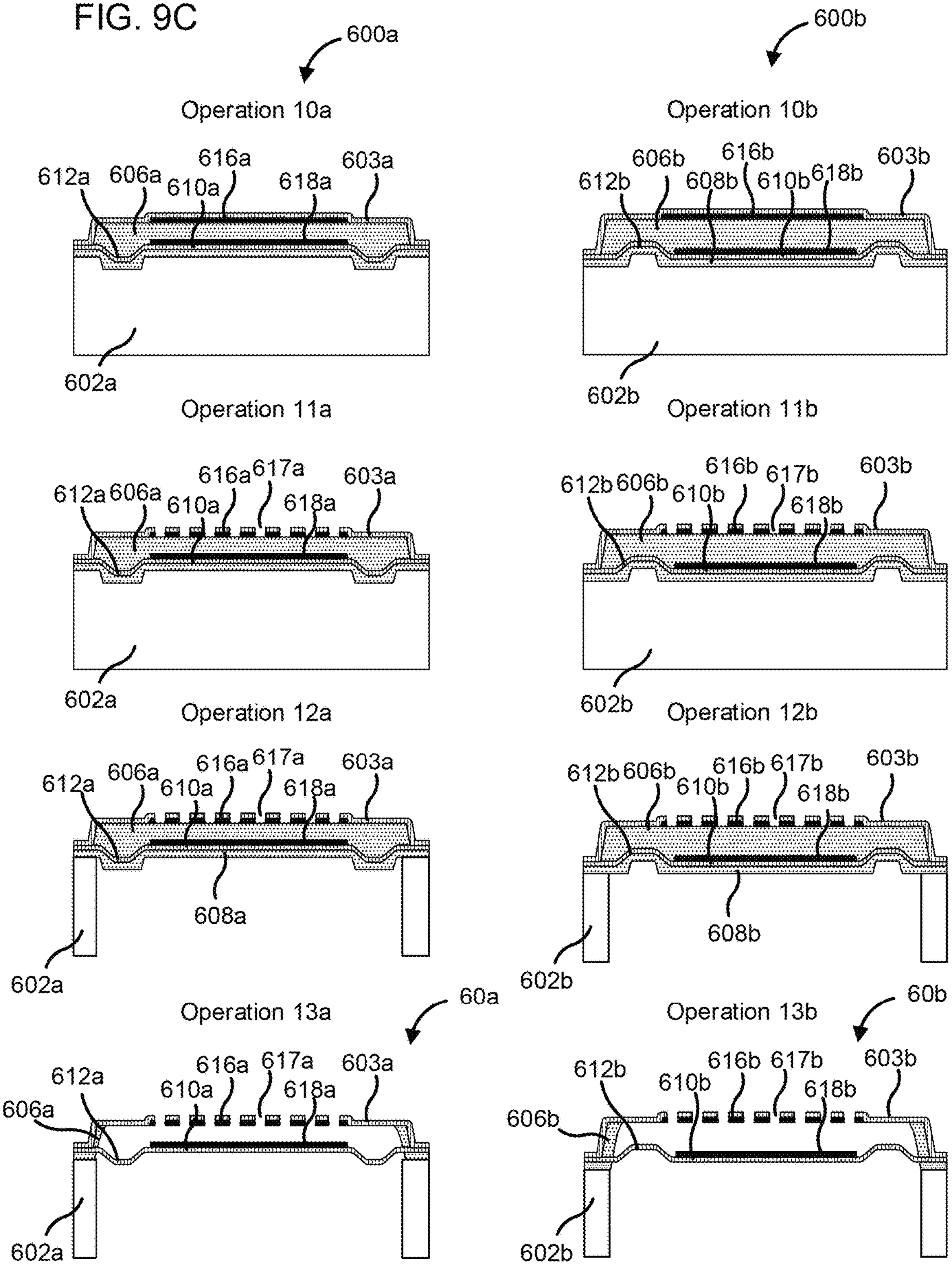

600a
600b
Operation 10a
612a
606a
610a
616a
618a
603a
602a
Operation 10b
612b
606b
608b
616b
610b
618b
603b
602b
Operation 11a
612a
606a
610a
616a
617a
618a
603a
602a
Operation 11b
612b
606b
610b
616b
617b
618b
603b
602b
Operation 12a
612a
606a
610a
616a
617a
618a
603a
608a
602a
Operation 12b
612b
606b
610b
616b
617b
618b
603b
608b
602b
Operation 13a
60a
612a
606a
610a
616a
617a
618a
603a
602a
Operation 13b
60b
612b
606b
610b
616b
617b
618b
603b
602b

FIG. 10

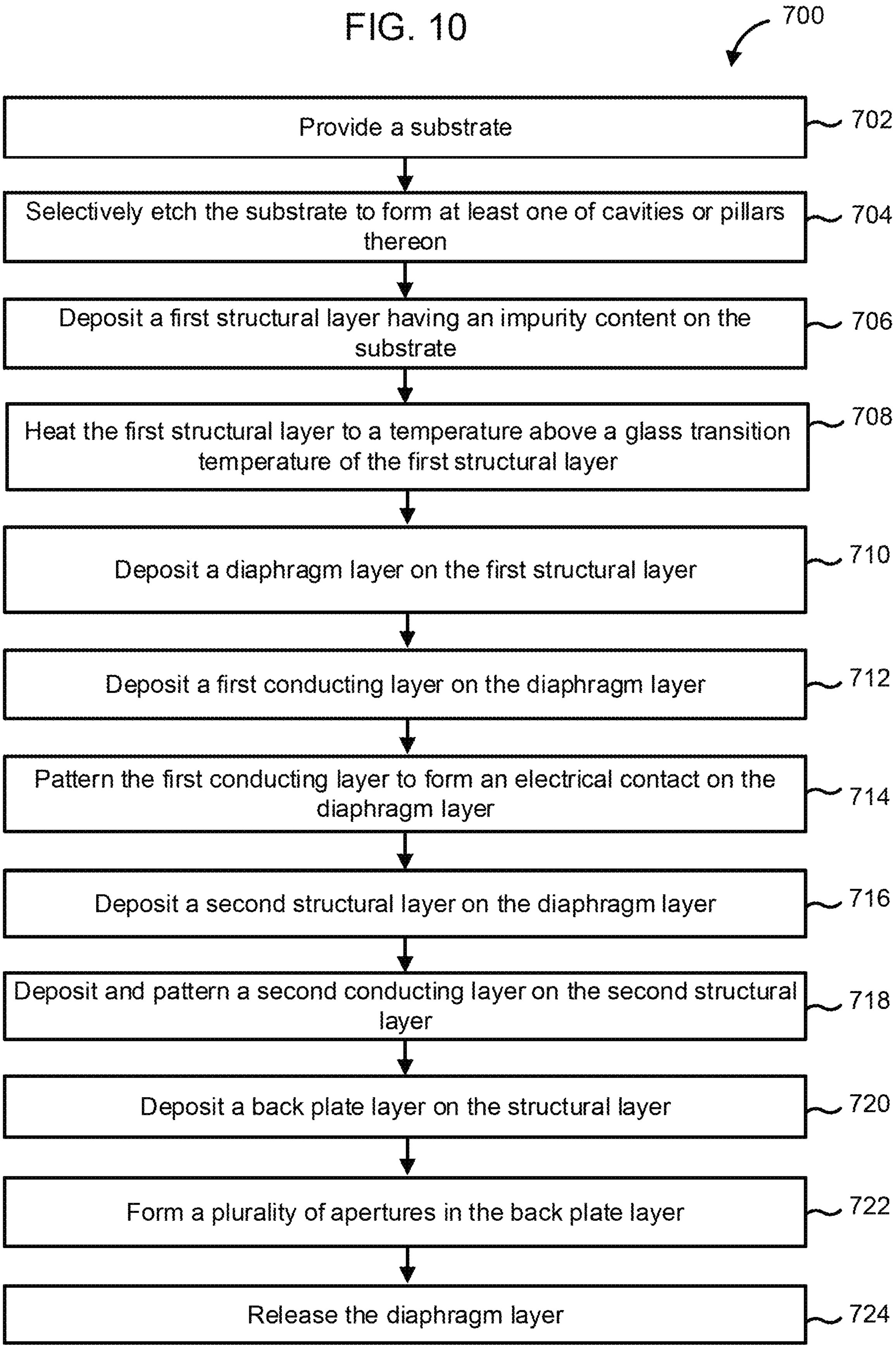

700
Provide a substrate
702
Selectively etch the substrate to form at least one of cavities or pillars thereon
704
Deposit a first structural layer having an impurity content on the substrate
706
Heat the first structural layer to a temperature above a glass transition temperature of the first structural layer
708
Deposit a diaphragm layer on the first structural layer
710
Deposit a first conducting layer on the diaphragm layer
712
Pattern the first conducting layer to form an electrical contact on the diaphragm layer
714
Deposit a second structural layer on the diaphragm layer
716
Deposit and pattern a second conducting layer on the second structural layer
718
Deposit a back plate layer on the structural layer
720
Form a plurality of apertures in the back plate layer
722
Release the diaphragm layer
724

FIG. 11A

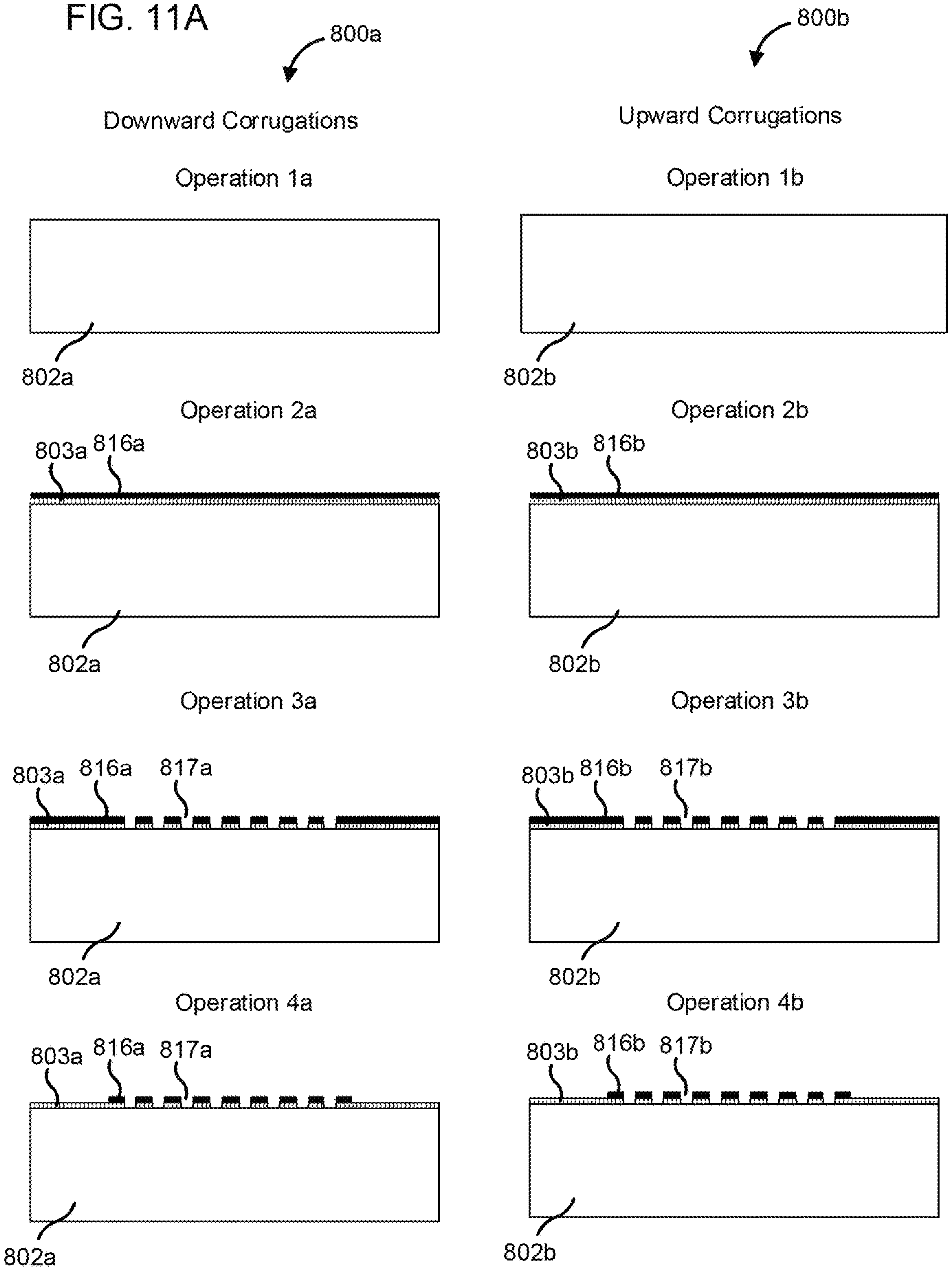

800a
800b
Downward Corrugations
Upward Corrugations
Operation 1a
Operation 1b
802a
802b
Operation 2a
Operation 2b
803a
816a
803b
816b
802a
802b
Operation 3a
Operation 3b
803a
816a
817a
803b
816b
817b
802a
802b
Operation 4a
Operation 4b
803a
816a
817a
803b
816b
817b
802a
802b

FIG. 11B

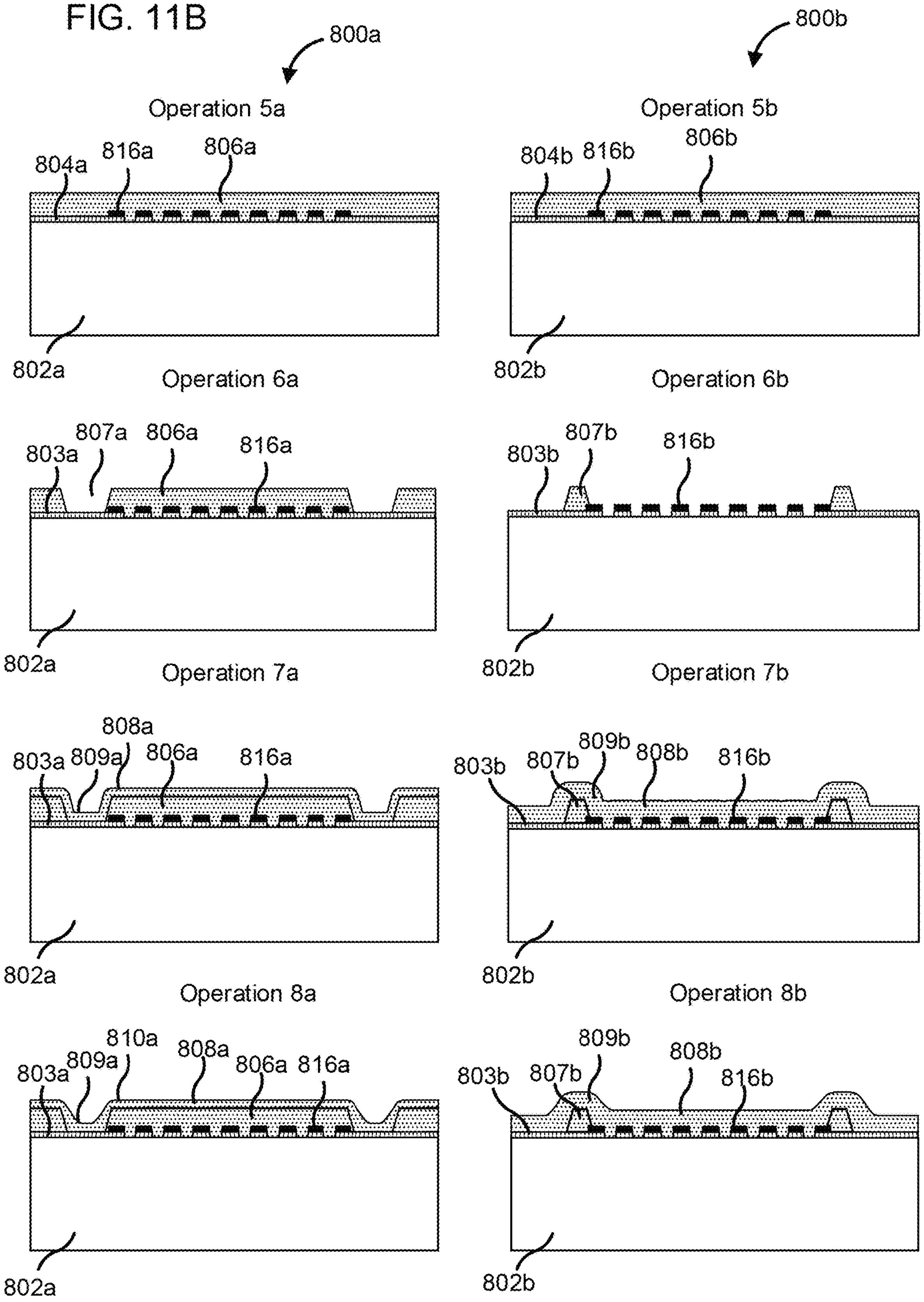

800a
800b
Operation 5a
804a
816a
806a
802a
Operation 5b
804b
816b
806b
802b
Operation 6a
803a
807a
806a
816a
802a
Operation 6b
803b
807b
816b
802b
Operation 7a
808a
803a
809a
806a
816a
802a
Operation 7b
803b
807b
809b
808b
816b
802b
Operation 8a
810a
803a
809a
808a
806a
816a
802a
Operation 8b
809b
803b
807b
808b
816b
802b

FIG. 11C

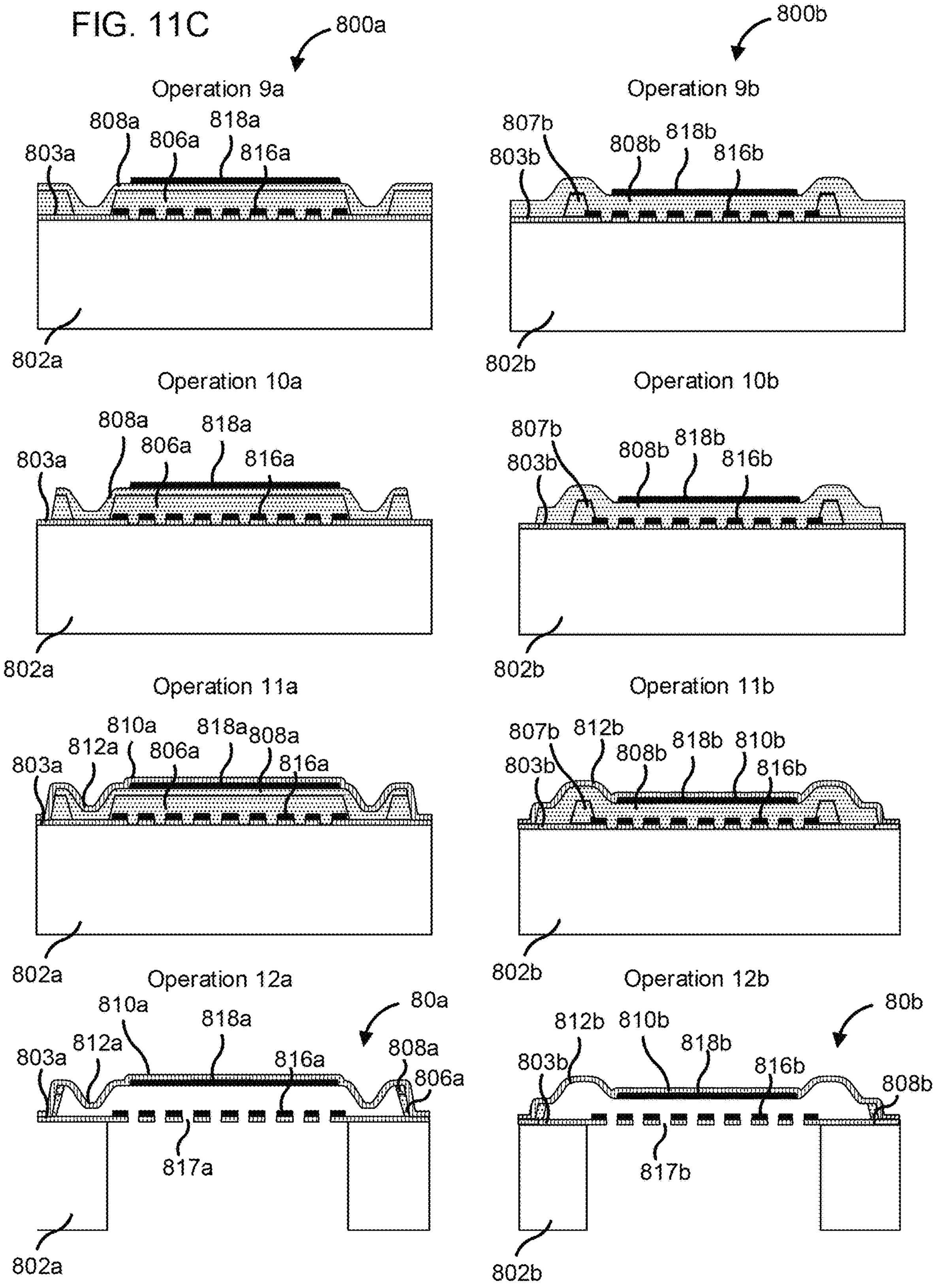

800a
800b
Operation 9a
808a
818a
806a
816a
803a
802a
Operation 9b
807b
808b
818b
816b
803b
802b
Operation 10a
808a
818a
806a
816a
803a
802a
Operation 10b
807b
803b
808b
818b
816b
802b
Operation 11a
810a
812a
818a
808a
806a
816a
803a
802a
Operation 11b
807b
812b
808b
818b
810b
803b
816b
802b
Operation 12a
80a
810a
818a
812a
816a
808a
803a
806a
817a
802a
Operation 12b
80b
812b
810b
818b
803b
816b
808b
817b
802b

FIG. 12A

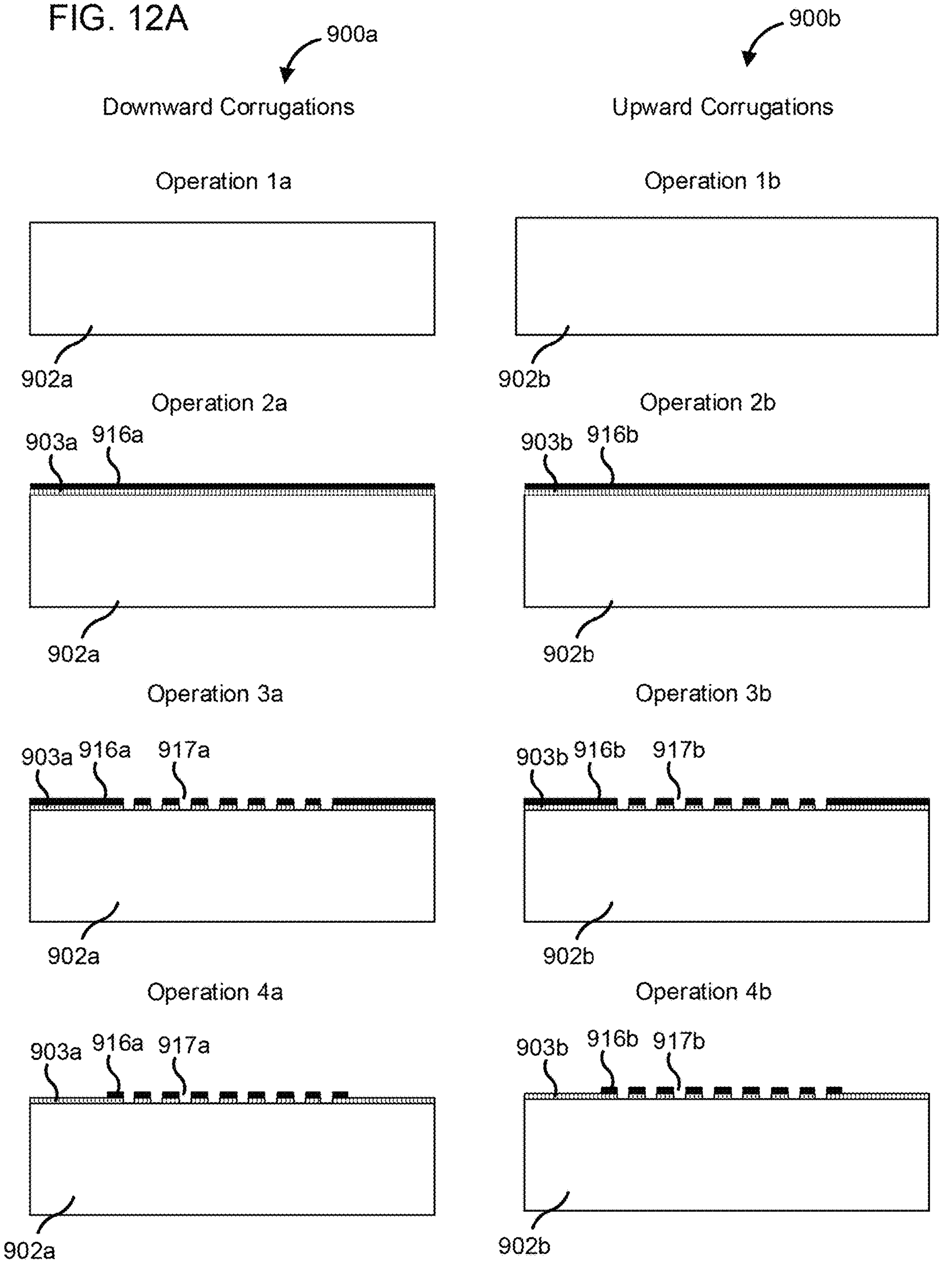

900a
Downward Corrugations
900b
Upward Corrugations
Operation 1a
902a
Operation 1b
902b
Operation 2a
903a
916a
902a
Operation 2b
903b
916b
902b
Operation 3a
903a
916a
917a
902a
Operation 3b
903b
916b
917b
902b
Operation 4a
903a
916a
917a
902a
Operation 4b
903b
916b
917b
902b

FIG. 12B

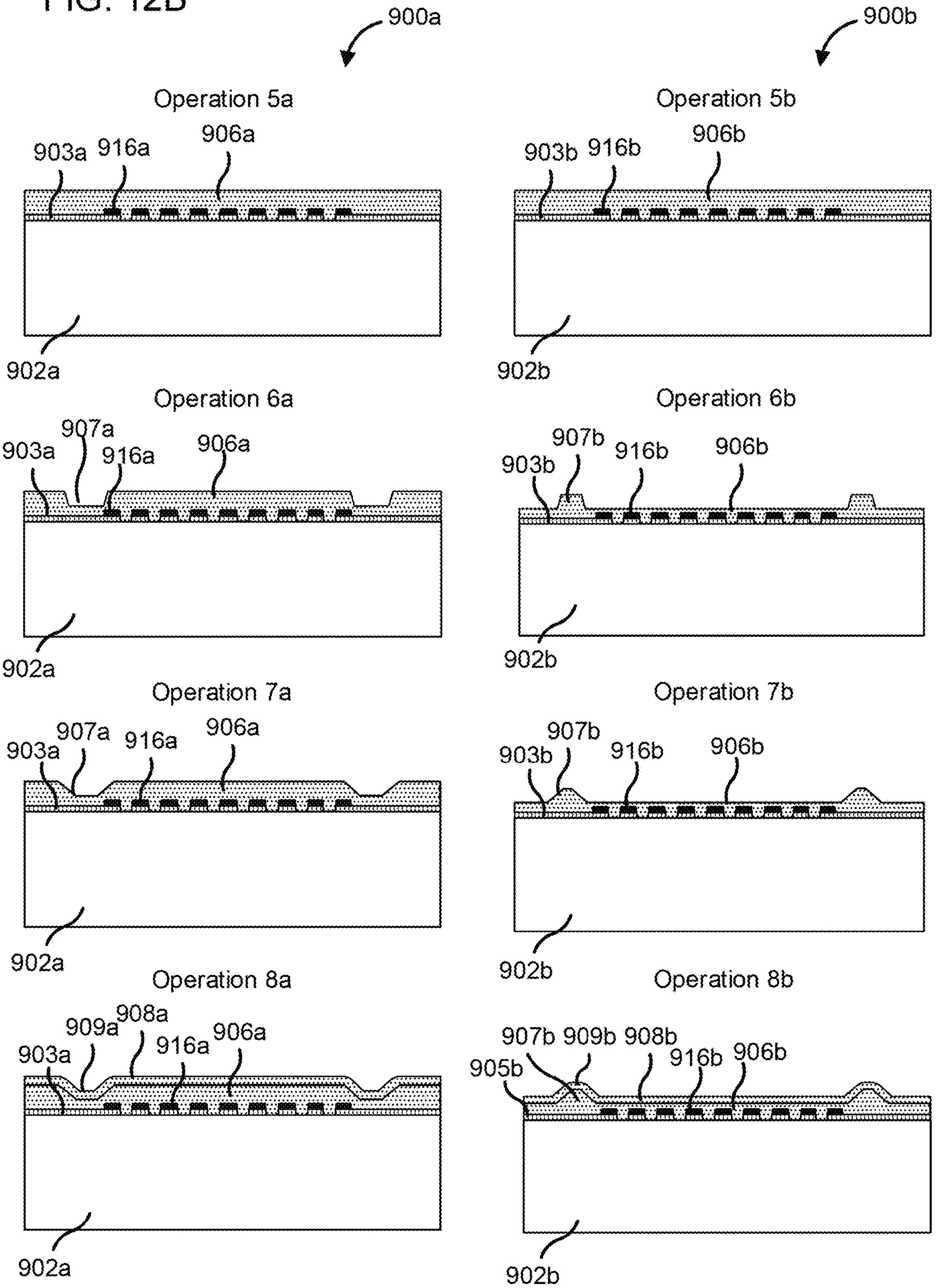

900a
900b
Operation 5a
903a
916a
906a
902a
Operation 5b
903b
916b
906b
902b
Operation 6a
903a
907a
916a
906a
902a
Operation 6b
903b
907b
916b
906b
902b
Operation 7a
903a
907a
916a
906a
902a
Operation 7b
903b
907b
916b
906b
902b
Operation 8a
903a
909a
908a
916a
906a
902a
Operation 8b
905b
907b
909b
908b
916b
906b
902b

FIG. 12C

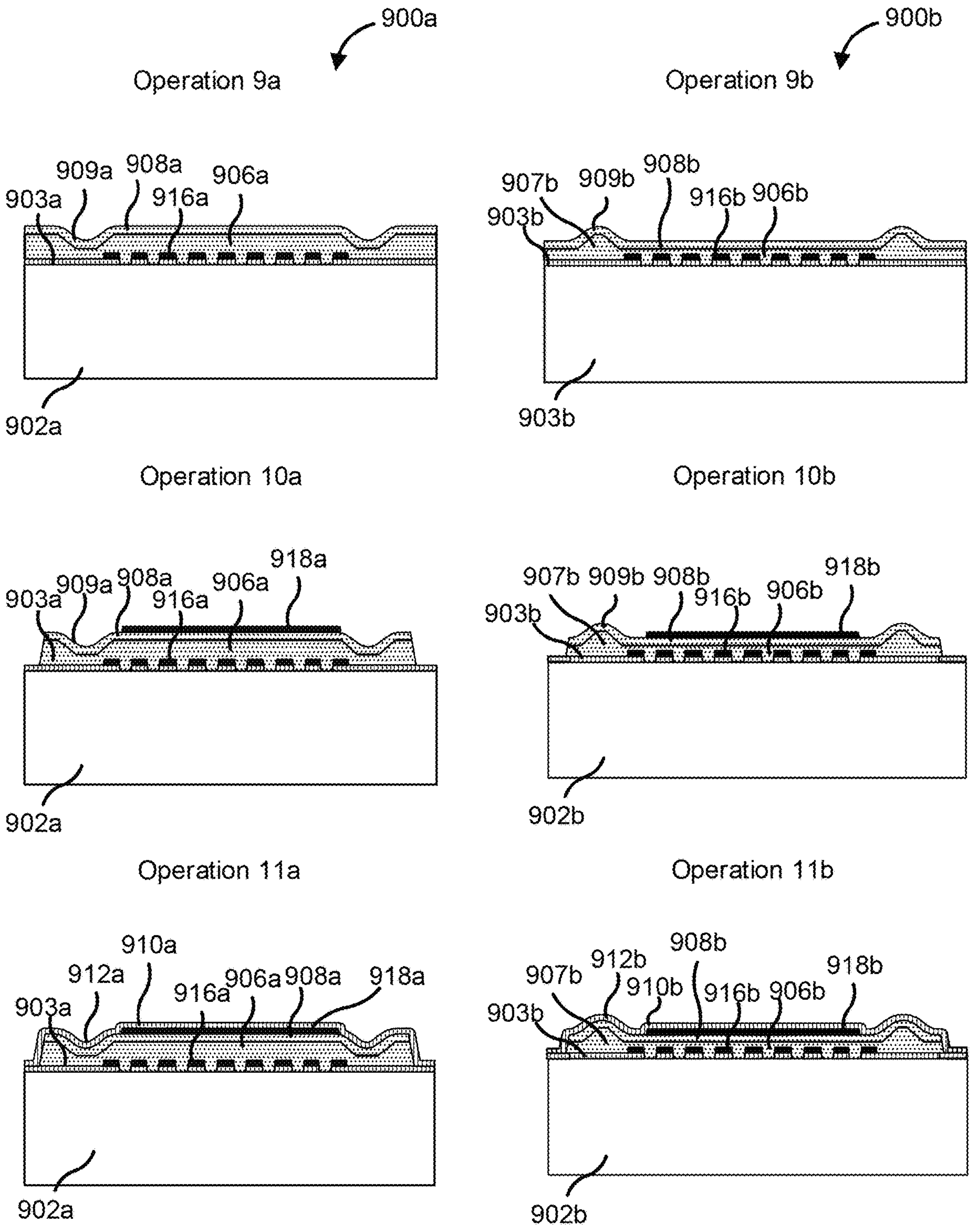
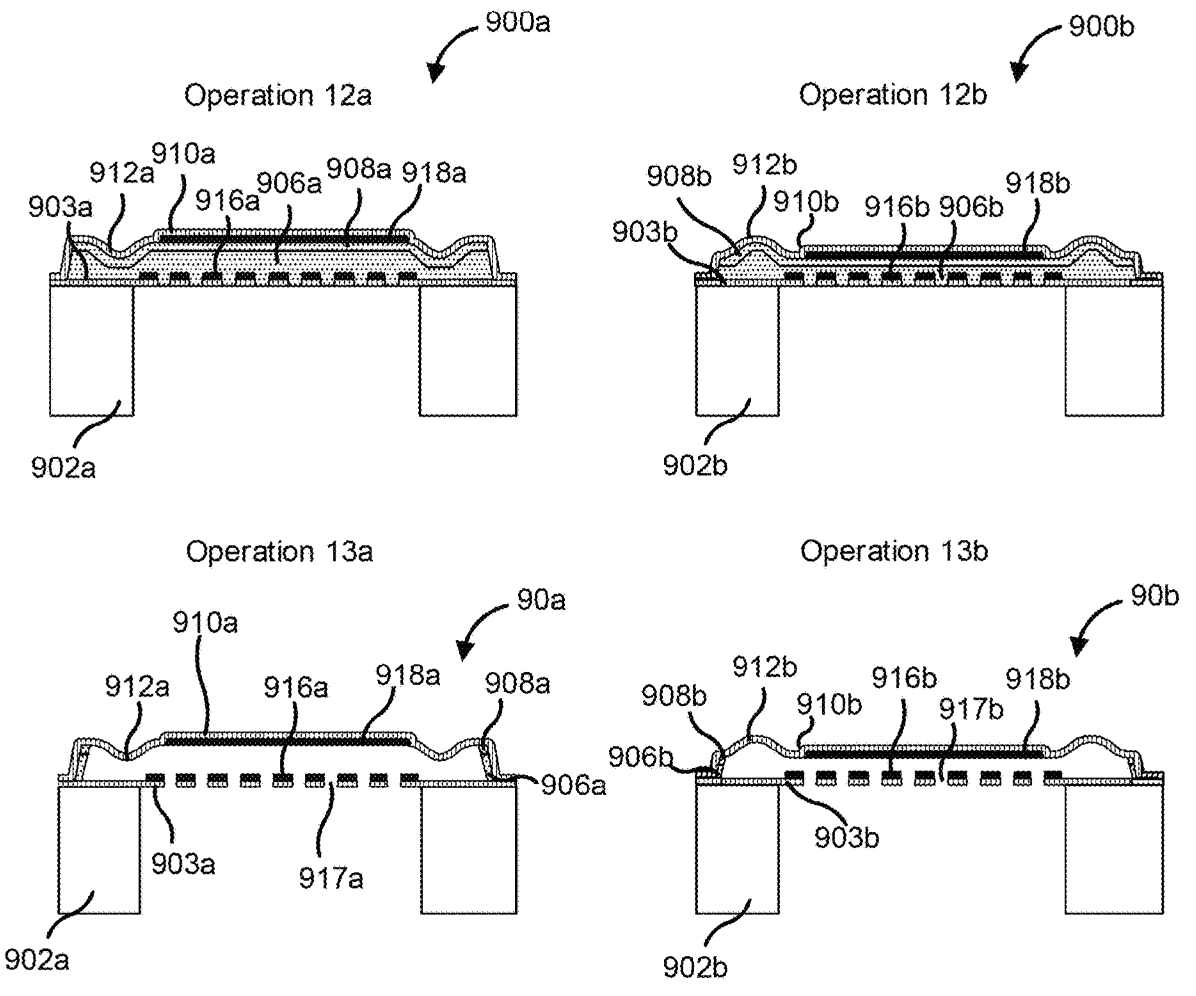

900a
900b
Operation 9a
Operation 9b
909a
908a
906a
903a
916a
902a
907b
909b
908b
916b
906b
903b
903b
Operation 10a
Operation 10b
918a
903a
909a
908a
916a
906a
902a
918b
907b
909b
908b
916b
906b
903b
902b
Operation 11a
Operation 11b
910a
912a
916a
906a
908a
918a
903a
902a
908b
912b
918b
907b
910b
916b
906b
903b
902b

FIG. 12D



Operation 12a

Operation 12b

Operation 13a

Operation 13b

FIG. 13A

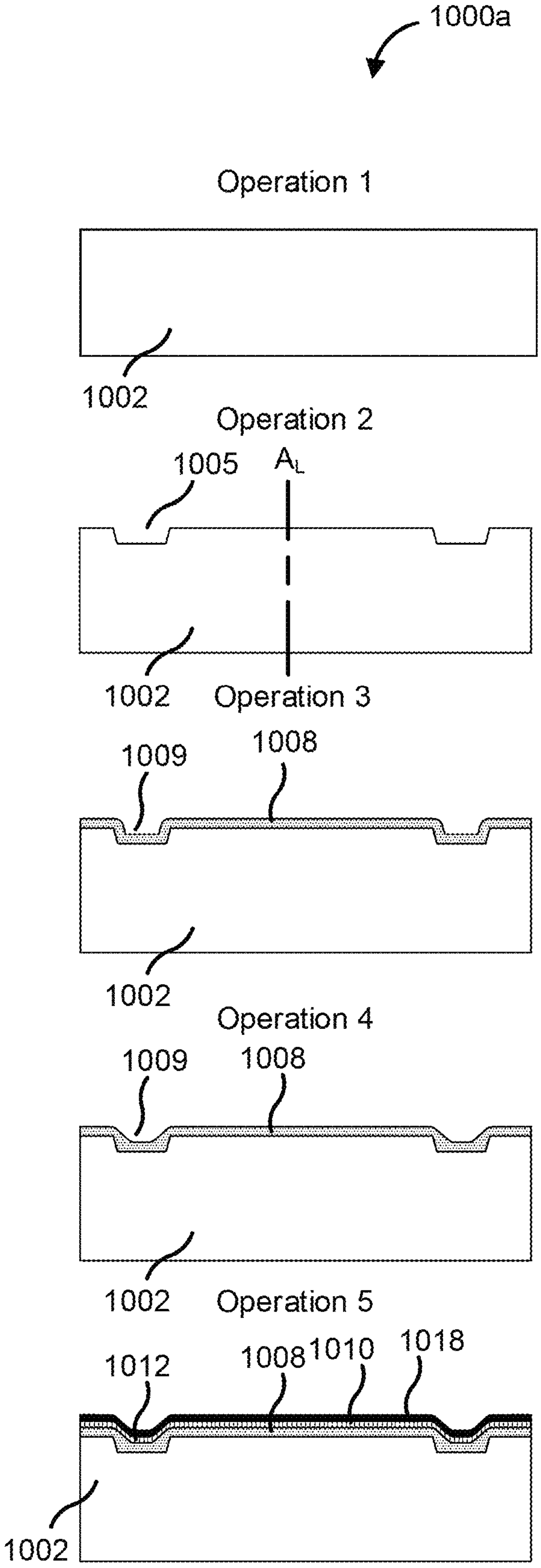
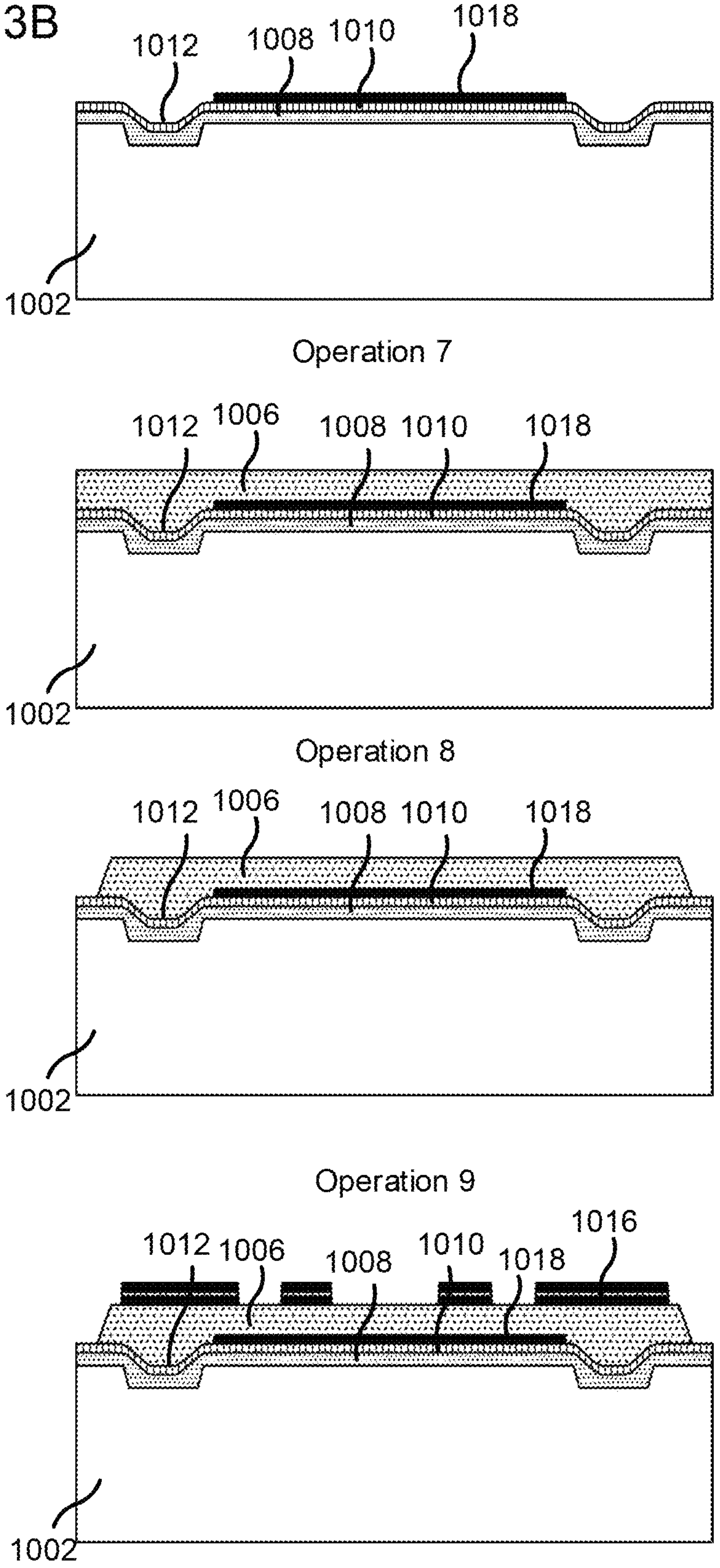

1000a
Operation 1
1002
Operation 2
1005
A_L
1002
Operation 3
1009
1008
1002
Operation 4
1009
1008
1002
Operation 5
1012
1008
1010
1018
1002

FIG. 13B

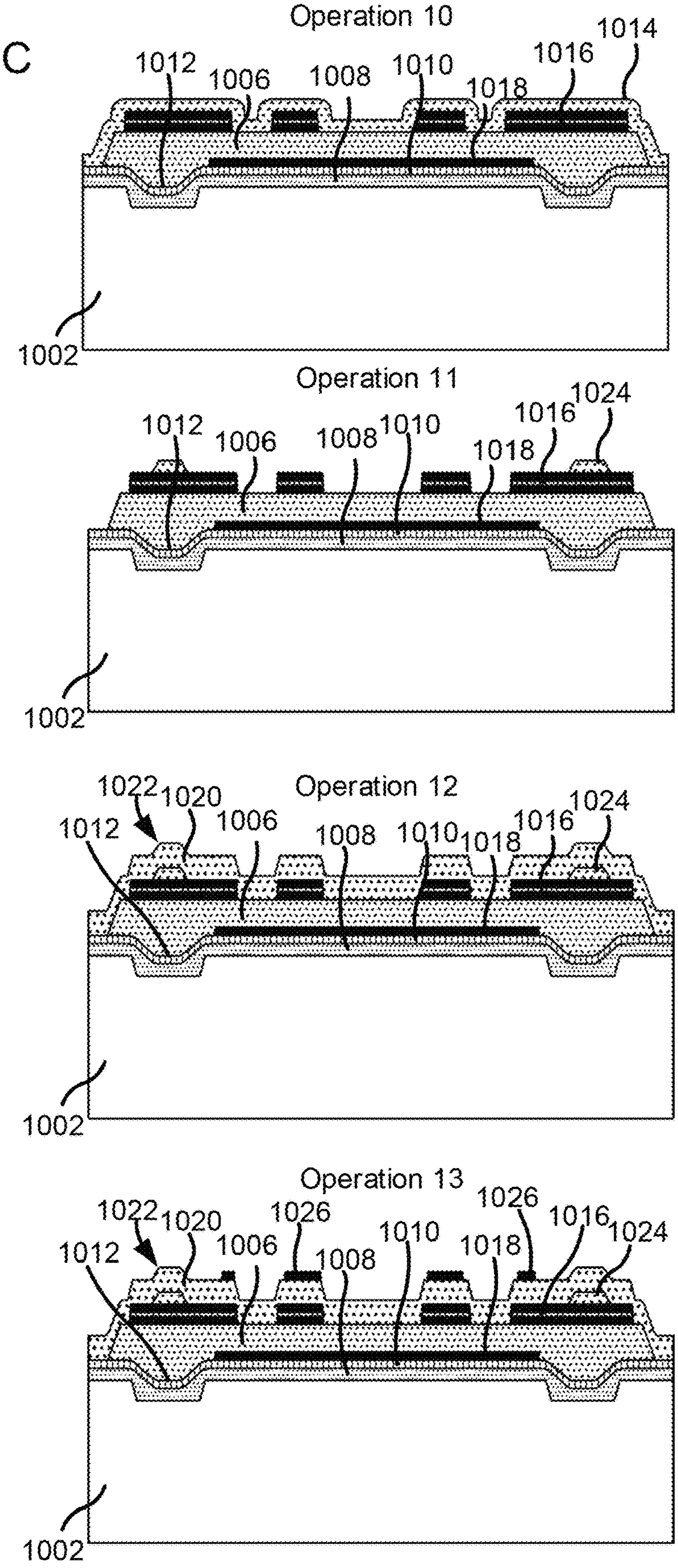

Operation 6

Operation 7

Operation 8

Operation 9

FIG. 13C


Operation 10

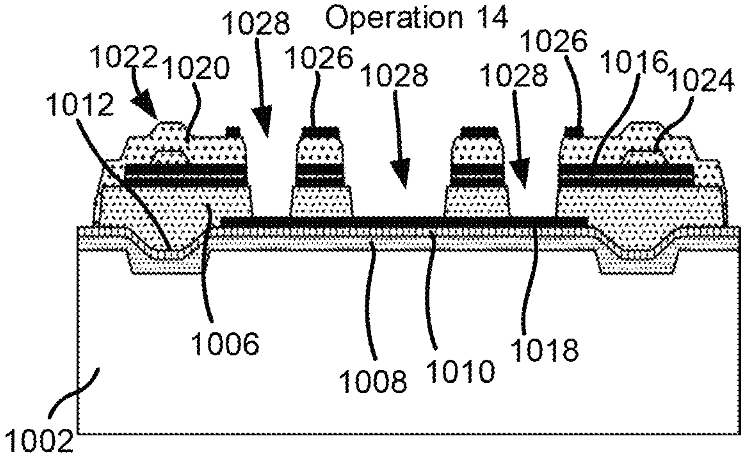
Operation 11

Operation 12

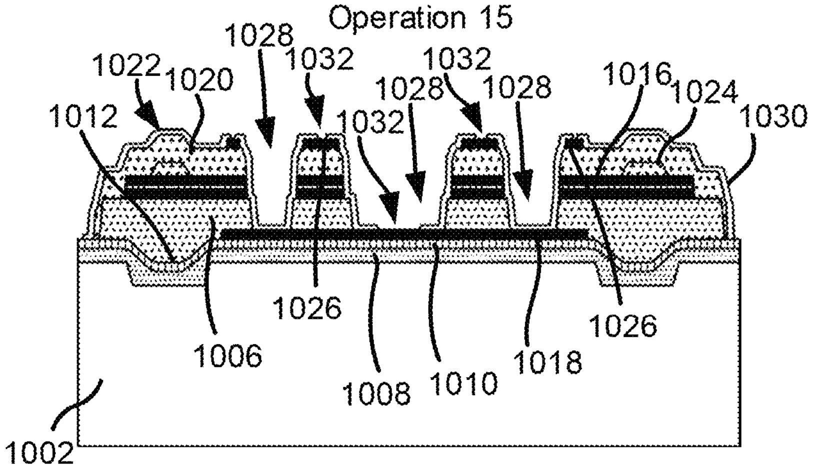
Operation 13

FIG. 13D

Operation 14



Operation 15



Operation 16

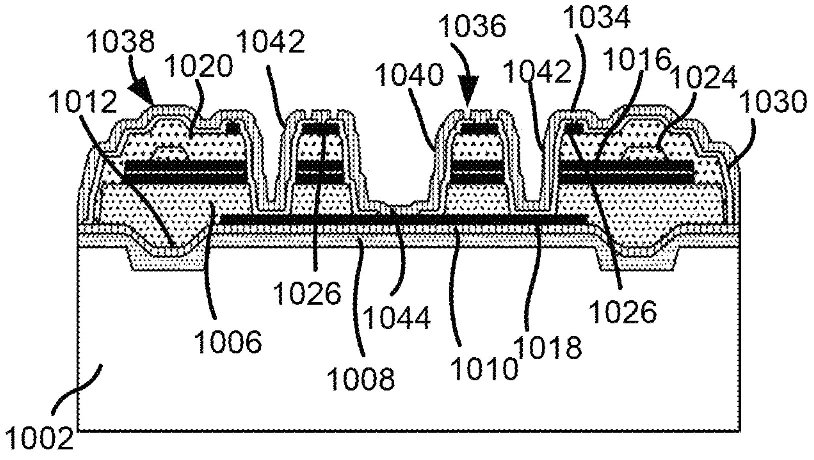
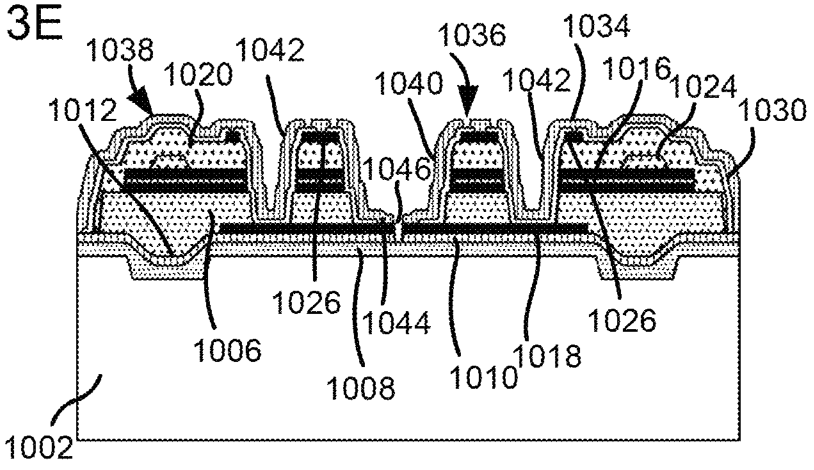
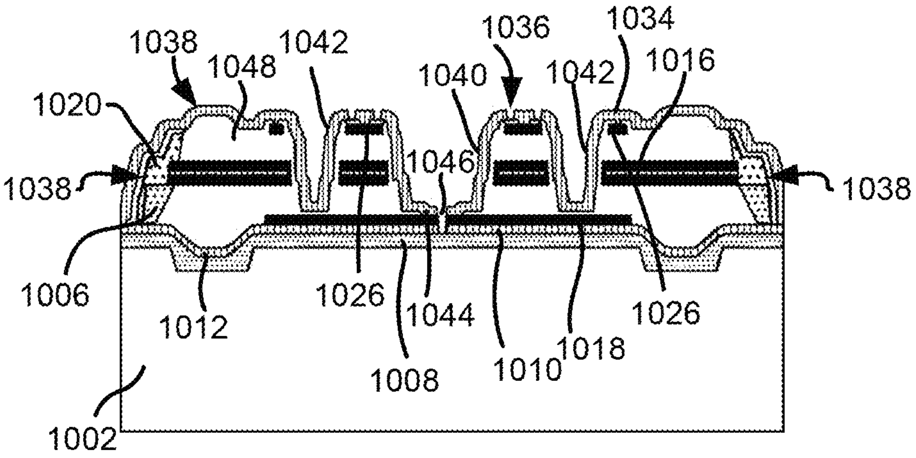


FIG. 13E

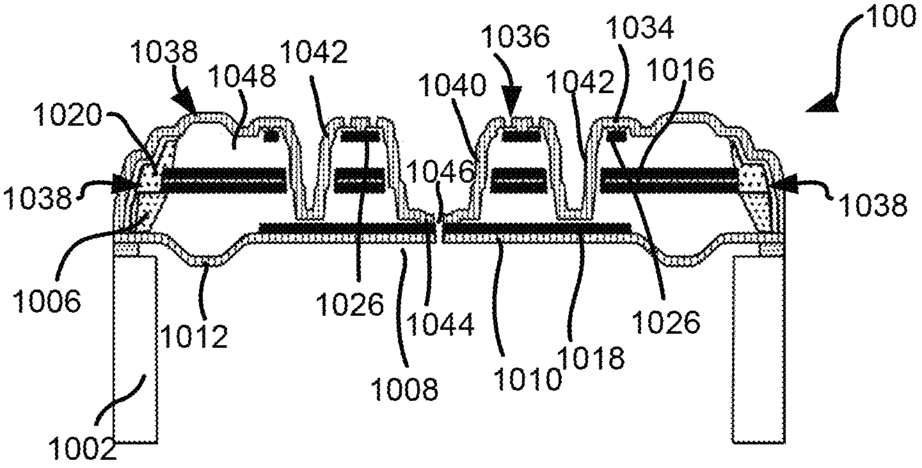
Operation 17



Operation 18



Operation 19



METHODS OF FORMING MEMS DIAPHRAGMS INCLUDING CORRUGATIONS

CROSS REFERENCE TO RELATED APPLICATIONS

The present application is a Continuation Application of U.S. application Ser. No. 16/593,498, filed Oct. 4, 2019, which claims priority to U.S. Provisional Application No. 62/742,164 filed Oct. 5, 2018, entitled "METHODS OF FORMING MEMS DIAPHRAGMS INCLUDING CORRUGATIONS," the entire disclosures of which are incorporated herein by reference in their entirety.

TECHNICAL FIELD

The present disclosure relates generally to systems and methods of improving compliance of diaphragms included acoustic transducers.

BACKGROUND

Microphone assemblies are generally used in electronic devices to convert acoustic energy to electrical signals. Microphones generally include diaphragms for converting acoustic signals to electrical signals. Pressure sensors may also include such diaphragms. Advancements in micro and nanofabrication technologies have led to the development of progressively smaller micro-electro-mechanical-system (MEMS) microphone assemblies and pressure sensors. Some microphones include tensioned or constrained diaphragms which may reduce the compliance of such diaphragms.

SUMMARY

Embodiments described herein relate generally to methods and processes for fabricating tensioned or constrained diaphragms for MEMS acoustic transducers that have enhanced compliance. In particular, methods and processes described enable fabrication of tensioned diaphragms that have one or more upward and/or downward facing corrugations for increasing a compliance of the diaphragm, the corrugations having smooth corners for reducing stress concentration, therefore increasing diaphragm robustness and reducing failure.

In some embodiments, a capacitive microelectromechanical systems (MEMS) die, comprises a substrate having a through-hole. A diaphragm having an annular corrugation is disposed between a substantially planar central portion and an outer portion, the substantially planar central portion having a conductive portion. The annular corrugation is defined by softened edges or corners at an interface between the annular corrugation and the central and outer portions of the diaphragm. The MEMS die has a back plate having a conductive portion. The back plate and the diaphragm are disposed in spaced-apart relation to form a capacitive structure located over the through-hole of, and supported by, the substrate. The corrugated diaphragm has more compliance than a diaphragm without corrugations.

In some embodiments, a method of fabricating a microelectromechanical systems (MEMS) die comprises forming a trench or a pillar by etching a first structural layer supported by a substrate. A second structural layer is deposited on the trench or pillar, the second structural layer including a depression corresponding to the trench or a bump corresponding to the pillar. Edges or corners of the depression or bump are softened. A diaphragm layer is deposited on the second structural layer after softening, the diaphragm layer including a downward facing corrugation corresponding to the depression or an upward facing corrugation corresponding to the bump. A diaphragm is formed by releasing a portion of the diaphragm layer including the corrugation from the second structural layer. The corrugated diaphragm has greater compliance than a diaphragm without corrugations.

In some embodiments, an acoustic transducer is formed by the process of providing a substrate, and selectively etching the substrate to form at least one of an enclosed trench or an enclosed pillar on the substrate. A first structural layer can be deposited on the substrate where the first structural layer includes at least one of a depression or a bump corresponding to the enclosed trench or the enclosed pillar. The first structural layer can be heated to a temperature above a glass transition temperature of the first structural layer causing the first structural layer to reflow. A diaphragm layer can be deposited over the first structural layer such that the diaphragm layer includes at least one of a downward facing corrugation corresponding to the depression or an upward facing corrugation corresponding to the bump formed in the first structural layer. The diaphragm can then be released, thereby forming a diaphragm suspended over the substrate.

BRIEF DESCRIPTION OF DRAWINGS

The foregoing and other features of the present disclosure will become more fully apparent from the following description and appended claims, taken in conjunction with the accompanying drawings. Understanding that these drawings depict only several implementations in accordance with the disclosure and are therefore, not to be considered limiting of its scope, the disclosure will be described with additional specificity and detail through use of the accompanying drawings.

FIGS. **1**A-**1**B are schematic illustrations of various operations included in a process for forming the diaphragm of an acoustic transducer including downward facing corrugations, according to an embodiment; FIG. **1**C is a plan view of the diaphragm of the acoustic transducer formed using the process of FIGS. **1**A-**1**B, with FIG. **1**B, operation **6** representing a side cross-section view of the FIG. **1**C taken along the line X-X in FIG. **1**C.

FIGS. **2**A-**2**B are schematic illustrations of various operations included in a process for forming the diaphragm of an acoustic transducer including upward facing corrugations, according to an embodiment; FIG. **2**C is a plan view of the diaphragm of the acoustic transducer formed using the process of FIGS. **2**A-**2**B, with FIG. **2**B, operation **6** representing a side cross-section view of the FIG. **2**C taken along the line Y-Y in FIG. **2**C.

FIG. **3** is a schematic flow diagram of a method for fabricating an acoustic transducer having a diaphragm having an upward or downward facing corrugation defined therein, according to an embodiment.

FIGS. **4**A-**4**C are schematic illustrations of various operations included in a process for forming an acoustic transducer including upward or downward facing corrugations, according to an embodiment.

FIGS. **5**A-**5**D are schematic illustrations of various operations included in a process for forming an acoustic transducer including upward or downward facing corrugations, according to an embodiment; FIG. **5**E is an enlarged view of a portion of the acoustic transducer of FIGS. **5**A-**5**D indicate by the arrow A in operation **14***a* of FIG. **5**D.

FIG. **6** is a top view of a portion of a back plate layer of the acoustic transducer of FIGS. **5**A-**5**D showing a plurality of apertures formed therein, according to an embodiment.

FIG. **7**, panel A is a table summarizing diaphragms including downward facing corrugations formed in two wafer lots using various methods, the shape of their edges (or corners) and associated pressure at which the diaphragms fail; FIG. **7**, panels B-E are scanning electron microscopy (SEM) images of representative samples of the two lots of wafers.

FIG. **8** is a plot of diaphragm strength of diaphragms formed in representative samples of the two lots of wafers of FIG. **7**A.

FIGS. **9**A-**9**C are schematic illustrations of various operations included in a process for forming an acoustic transducer including upward or downward facing corrugations, according to an embodiment.

FIG. **10** is a schematic flow diagram of a method for fabricating an acoustic transducer having a diaphragm having an upward or downward facing corrugation defined therein, according to another embodiment.

FIGS. **11**A-**11**C are schematic illustrations of various operations included in a process for forming an acoustic transducer including upward or downward facing corrugations, according to an embodiment.

FIGS. **12**A-**12**D are schematic illustrations of various operations included in a process for forming an acoustic transducer including upward or downward facing corrugations, according to an embodiment.

FIGS. **13**A-**13**E are schematic illustrations of various operations included in a process for forming an acoustic transducer including two diaphragms with corrugations, according to an embodiment.

Reference is made to the accompanying drawings throughout the following detailed description. In the drawings, similar symbols typically identify similar components, unless context dictates otherwise. The illustrative implementations described in the detailed description, drawings, and claims are not meant to be limiting. Other implementations may be utilized, and other changes may be made, without departing from the spirit or scope of the subject matter presented here. It will be readily understood that the aspects of the present disclosure, as generally described herein, and illustrated in the figures, can be arranged, substituted, combined, and designed in a wide variety of different configurations, all of which are explicitly contemplated and made part of this disclosure.

DETAILED DESCRIPTION OF VARIOUS EMBODIMENTS

Embodiments described herein relate generally to methods and processes for fabricating tensioned or constrained diaphragms for MEMS acoustic transducers that have enhanced compliance. In particular, methods and processes described enable fabrication of tensioned diaphragms that have one or more upward and/or downward facing corrugations for increasing a compliance of the diaphragm, the corrugations having smooth corners for reducing stress concentration, therefore increasing diaphragm robustness and reducing failure.

Many acoustic transducers include one or more diaphragms suspended above a back plate, below a back plate or having a back plate interposed therebetween. In some acoustic transducers, the diaphragm may be tensioned or constrained to provide high linearity. However, such tensioned diaphragms may not have sufficiently high compliance, which may cause low sensitivity or movement of the diaphragms in situations in which the acoustic transducer is exposed to sound pressures. Corrugations or ridges, for example, upward or downward facing corrugations, may be formed in such tensioned diaphragms for increasing compliance thereof. Some fabrication processes may yield corrugations having sharp corners (i.e., having a radius of curvature less than 1 μm). Stress may concentrate at such sharp corners, for example, during shock and high pressure events, causing diaphragm failure and reduced robustness.

In contrast, methods and processes described herein provide benefits including, for example: (1) enabling fabrication of diaphragms including corrugations having smooth or rounded corners (i.e., having a radius of curvature at the corners of greater than 1 μm and less than 50 μm) so as to reduce stress concentration and increase robustness; (2) using a simple PSG reflow process to smooth corners in depressions or bumps formed in the PSG layer which serves as a template or mold to form the diaphragm having corrugations with smooth corners; (3) easy integration with current fabrication methods, thereby reducing fabrication complexity and cost; and (4) allowing fabrication of upward facing corrugations, downward facing corrugations or a combination thereof.

As described herein, the terms "downward facing corrugations" refer to corrugations or ridges projecting from the diaphragm towards a substrate on which the diaphragm is suspended, and "upward facing corrugations" refer to corrugations or ridges projecting from the diaphragm away from the substrate.

FIGS. **1**A-**1**B illustrate a process flow **100** for forming an acoustic transducer **10** having a diaphragm **110** including downward facing corrugations or ridges **112**, according to an embodiment. The acoustic transducer **10** may include, for example, a MEMS acoustic transducer for use in a MEMS microphone assembly or a MEMS pressure sensor and may be configured to generate electrical signals in response to acoustic signals or atmospheric pressure changes.

At operation **1**, a substrate **102** including a first structural layer **104** disposed thereon is provided. The substrate **102** may include, for example, silicon, glass, Pyrex, quartz or any other substrate described herein. The first structural layer **104** may include a first PSG or BPSG layer having a first impurity content, for example, a first phosphorus content in a range between 2% and 6% and may be deposited over the substrate **102** using CVD, LPCVD, PECVD, ALD, any other suitable method or a combination thereof.

At operation **2**, one or more enclosed trenches **105** are formed in the first structural layer **104**. The enclosed trenches **105** may be formed using a wet etch (e.g., a BHF etch) or a dry etch (e.g., RIE or DRIE etch). The etch may cause the enclosed trenches **105** to have sharp corners and edges. In some embodiments, the one or more enclosed trenches **105** may have a circular cross-section, for example, define a circular trench etched about a longitudinal axis A_L of the substrate **102**.

At operation **3**, a second structural layer **108** is deposited on the first structural layer **104** such that the second structural layer **108** includes one or more depressions **109** corresponding to the one or more enclosed trenches **105** defined in the first structural layer **104**. The depressions **109** formed in the cavities may also have sharp corners and edges corresponding to the sharp edges or corners of the enclosed trenches **105** defined in the first structural layer **104**. The second structural layer **108** may include a second PSG layer having a second impurity content, for example, a second phosphorus content.

The second structural layer **108** may have a second phosphorus content larger than the first phosphorus content of the first PSG layer **104**, for example, in a range between 4% and 10%. The higher phosphorus content in the second structural layer **108** causes the second structural layer **108** to have a lower glass transition temperature than the first structural layer **104**. At operation **4**, the second structural layer **108** is heated to a temperature above the glass transition temperature thereof, but below a glass temperature of the first structural layer **104** causing only the second structural layer **108** to reflow, thereby smoothing or rounding the corners and edges of the depressions **109**.

At operation **5**, a diaphragm layer **110** is deposited on the second structural layer **108** such that the diaphragm layer **110** includes one or more downward facing corrugations **112** projecting therefrom towards the substrate **102**. Furthermore, the downward facing corrugations **112** include smooth or rounded corners **113** corresponding to the smooth corners of the depressions **109**.

At operation **6**, at least a portion of the substrate **102**, the first structural layer **104** and the second structural layer **108** is etched so as to leave a diaphragm **110** having downward facing corrugations **112** suspended over the substrate **102**, thereby forming the acoustic transducer **10**. In some embodiments, the downward facing corrugations **112** may include circumferential corrugations, for example, corresponding to circular enclosed trenches **105** initially formed in the first structural layer **104**. FIG. **1**C shows a plan view of the diaphragm **110** showing the downward facing corrugation **112**. While shown as including a pair of corrugations **112**, any number of corrugations may be formed in the diaphragm **110**. In various embodiments, the corrugations **112** may have a depth in a range of 0.5 microns to 5 microns (e.g., 0.5, 1, 2, 3, 4 or 5 microns inclusive of all ranges and values therebetween).

FIGS. **2**A-**2**B illustrates a process flow **200** for forming an acoustic transducer **20** having a diaphragm **210** including upward facing corrugations **212**, according to an embodiment. The acoustic transducer **20** may include, for example, a MEMS acoustic transducer for use in a MEMS microphone assembly or a MEMS pressure sensor and may be configured to generate electrical signals in response to acoustic signals or atmospheric pressure changes.

At operation **1**, a substrate **202** including a first structural layer **204** disposed thereon is provided. The substrate **202** may include, for example, glass, silicon, Pyrex, quartz or any other substrate described with respect to the method **300**, **700**. The first structural layer **204** may have an impurity, for example, a first amount of phosphorus or first phosphorus content in a range between 2% and 6% and may be deposited over the substrate **202** using CVD, LPCVD PECVD, ALD, any other suitable method or a combination thereof.

At operation **2**, one or more enclosed pillars **205** are formed in the first structural layer **204**. The enclosed pillar **205** may be formed using a wet etch (e.g., a BHF etch) or a dry etch (e.g., RIE or DRIE etch) to remove large portions of the first structural layer **204**, leaving the enclosed pillar **205** standing on the substrate **202**. The enclosed pillar **205** may, for example, define an enclosed circular pillar formed about a longitudinal axis A_L of the substrate **202** and extending towards the substrate **202**. The etch may cause the enclosed pillars **205** to have sharp corners and edges. At operation **3**, a second structural layer **208** is deposited on the substrate and the enclosed pillar **205** formed from the first structural layer **204** such that the second structural layer **208** includes one or more bumps **209** corresponding to the one or more pillars. The bumps **209** formed on the enclosed pillar **205** may also have sharp corners and edges corresponding to the sharp edges or corners of the enclosed pillar **205** defined from the first structural layer **204**.

The second structural layer **208** may have a second impurity content, for example, a second phosphorus content larger than the first phosphorus content of the first structural layer **204**, for example, in a range between 4% and 10% and thereby, a lower glass transition temperature than the first structural layer **204**. At operation **4**, the second structural layer **208** is heated to a temperature above the glass transition temperature thereof, but below a glass temperature of the first structural layer **204** causing only the second structural layer **208** to reflow, thereby smoothing or rounding the corners and edges of the bumps **209**.

At operation **5**, a diaphragm layer **210** is deposited on the second structural layer **208** such that the diaphragm layer **210** includes one or more upward facing corrugations **212** projecting therefrom away from the substrate **202**. Furthermore, the upward facing corrugations **212** include smooth or rounded corners **213** corresponding to the smooth corners of the bumps **209**. At operation **6**, at least a portion of the substrate **202** and the first structural layer **204** as well as the pillars **205** are etched so as to leave the diaphragm layer **210** forming a diaphragm having upward facing corrugations **212** suspended over the substrate **202**, thereby forming the acoustic transducer **20**. In some embodiments, the upward facing corrugations **212** include enclosed circumferential corrugations and may have a height in a range of 0.5 microns to 5 microns (e.g., 0.5, 1, 2, 3, 4 or 5 microns inclusive of all ranges and values therebetween). For example, FIG. **2**C shows a plan view of the diaphragm **210** showing the upward facing corrugation **212** formed as an enclosed circular wall or pillar extending away from the substrate **202**.

FIG. **3** is a schematic flow diagram of an example method **300** for fabricating an acoustic transducer (e.g., the acoustic transducer **10**, **20**, **40**, **50**, **80**, **90**) including a diaphragm that includes upward or downward facing corrugations having smooth or rounded corners. The acoustic transducer may include, for example, a MEMS acoustic transducer for use in a MEMS microphone assembly or a MEMS pressure sensor, and may be configured to generate electrical signals in response to acoustic signals or atmospheric pressure changes.

The method comprises providing a substrate, at **302**. The substrate may be formed from silicon, silicon oxide, glass, Pyrex, quartz, ceramics, or any other suitable material, and may include the substrate **102**, **202**, **402** or **502**, or **802** as described herein in detail with respect to processes **100**, **200**, **400**, **500**, or **800**. In some embodiments, a back plate layer (e.g., the back plate layer **403**, **503**) is deposited on the substrate layer, at **304**. The back plate layer may be formed from a low stress material, for example low stress silicon nitride (LSN), low stress oxide or any other suitable material. The back plate layer may be deposited using physical vapor deposition (PVD), chemical vapor deposition (CVD), low pressure chemical vapor deposition (LPCVD), plasma enhanced CVD (PECVD), atomic layer deposition (ALD), any other suitable process or a combination thereof. The back plate layer may be relatively inflexible relative to a diaphragm to be formed on the substrate.

In some embodiments, a first conducting layer (e.g., the first conducting layer **416**, **516**, **816**, **916** described with respect to the process **400**, **500**, **800**, **900**) is deposited on the back plate layer, at **306**. In some embodiments, the first conducting layer may be formed from polysilicon (poly). In other embodiments, the first conducting layer may be formed from metals (e.g., gold, platinum, etc.), doped silicon or any other suitable conductive material. The first conducting layer may be deposited using PVD, thermal evaporation, e-beam evaporation, CVD, PECVD, LPCVD, ALD, or any other suitable process or a combination thereof.

At **308**, apertures may be formed through the back plate layer and the first conducting layer. For example, a wet etching process or a dry etching process (e.g., reactive ion etching (ME), deep RIE (DRIE), focused ion beam etching (FIB), etc.) or any other suitable etching process may be used to form corresponding apertures in the back plate and the first conducting layer. The apertures may have any suitable shape, for example, square, rectangular, oblong, circular, oval, polygonal (e.g., hexagonal, octagonal, etc.) or any other suitable shape.

At **310**, the first conducting layer may be selectively etched (e.g., using a wet or dry etching process) to form an electrical contact on the back plate. For example, the radial or circumferential etches of the first conducting layer may be selectively etched to form the electrical contact on the back plate.

At **312**, a first structural layer is deposited on the substrate. In various embodiments, the first structural layer may include a first PSG layer having a first phosphorus content. For example, the first PSG layer **406**, **506**, **806**, **906** may be deposited on the substrate. In other embodiments, the structural layer may include a borophosphosilicate glass (BPSG) layer, an oxide, a nitride or any other suitable material.

At **314**, the first structural layer is selectively etched to form one or more enclosed trenches or pillars in the structural layer. In some embodiments, the first structural layer (e.g., a first PSG layer) is selectively etched using a wet etch process (e.g., using buffered hydrofluoric acid (BHF)) up to the back plate layer, such that portions of the structural layer in the areas being etched is completely removed (e.g., as described herein with respect to the process **100**, **200**, **400**, **800**). In such embodiments, the back plate layer may serve as an etch stop for the wet etch process. In other embodiments, the structural layer may be selectively etched using a timed dry etch process (e.g., an RIE or DRIE process) such that the dry etch does not reach the back plate layer (e.g., as described herein with respect to the process **500**, **900**). For example, the dry etch process may be performed for a predetermined time such that a portion of the first structural layer remains disposed over the substrate or, in some embodiments, the back plate layer. The enclosed trenches or enclosed pillars defined in the first structural layer may have sharp corners (e.g., having a radius of curvature less than 1 μm). In some embodiments in which the first structural layer comprises a first PSG layer, the first PSG layer may be heated above a glass transition temperature thereof causing the first PSG layer to reflow, thereby rounding the corners of the first PSG layer (e.g., cause the corners to have a radius of curvature of greater than 1 μm and less than 50 μm).

At **316**, a second structural layer having an impurity content, for example, a second PSG layer (e.g., the second PSG layer **108**, **208**, **408**, **508**, **808**, **908**) having a phosphorus content is deposited on the first structural layer. The second structural layer may be conformally deposited (i.e., uniformly disposed so as to adhere to the contours of the underlying first structural layer) such that the second structural layer includes one or more depressions or bumps corresponding to the one or more cavities or pillars, respectively already formed in the first structural layer. In some embodiments, the impurity may comprise phosphorus such that the phosphorus content is greater than 2%.

At **318**, the second structural layer is heated above a glass transition temperature of the second structural layer causing the second structural layer to reflow. Expanding further, the enclosed trenches or pillars formed in the structural layer at operation **314** may have sharp corners and edges (e.g., having a radius of curvature of less than 1 μm). Since the second structural layer is conformally deposited on the first structural layer, the second structural layer follows the contours of the first structural layer such that the depressions and or bumps included in the second structural layer also has the sharp corners and edges. Heating the second structural layer above the glass transition temperature causes a phase change in the second structural layer allowing it to reflow. The reflowing smoothens or rounds the corners and edges of the depressions or bumps formed in the second structural layer such that the corners and edges of the second structural layer may have a radius of curvature greater than 1 μm and less than 50 μm.

In some embodiments, the first structural layer is formed of PSG having a first phosphorus content, and the second structural layer is formed of PSG having a second phosphorus content different than the first phosphorus content. In other embodiments, the first phosphorus content may be equal to the second phosphorus content.

In some embodiments, the first phosphorus content included in the first structural layer may be between 2% and 6% and the second phosphorus content included in the second structural layer may be between 4% and 10%. In such embodiments, the second structural layer may have a higher amount of phosphorus than the first structural layer. The higher amount of phosphorus lowers the glass transition temperature of the second structural layer relative to a glass transition temperature of the first structural layer. The heating may be performed to a temperature which is higher than the glass transition temperature of the second structural layer but lower than the glass transition temperature of the first structural layer, thus causing only the second structural layer to flow and rounding the corners thereof, without causing the first structural layer to reflow.

In other embodiments, the first phosphorus content included in the first structural layer is between 4% and 10% and the second phosphorus content in the second structural layer is between 2% and 6% such that the second structural layer has a lower phosphorus content and, therefore a higher glass transition temperature than the first structural layer. In such embodiments, the first structural layer may be heated to a glass transition temperature thereof before the depositing the second structural layer on the first structural layer. In some embodiments, second structural layer may be heated to a temperature which is greater than a glass transition temperature of each of the first structural layer and the second structural layer so as to cause each of the first and second structural layers to reflow. This may yield smoother corners and edges in the second structural layer.

At **322**, a diaphragm layer is deposited on the second structural layer such that the diaphragm layer includes downward facing corrugations corresponding to the one or more depressions, upward facing corrugations corresponding to the one or more bumps formed in the second structural layer or a combination thereof. For example, a low stress material, for example LSN or a low stress ceramic may be deposited on the second structure layer (e.g., via a physical or chemical vapor deposition process). In other embodiments, the diaphragm layer may include a dielectric or conductive material (e.g., silicon oxide, silicon nitride, silicon carbide, gold, aluminum, platinum, etc.). The second structural layer acts as a mold or template for the diaphragm layer such that each of the downward facing corrugations or upward facing corrugations defined in the diaphragm layer have a radius of curvature corresponding to the second radius of curvature, i.e. radius of curvature after reflow. In this manner, the stress concentration is reduced at the edges or corners of the corrugations increasing robustness and shock resistance.

In some embodiments, before depositing a diaphragm layer on the second structural layer, a second conducting layer is deposited and patterned on the second structural layer, at **320**. The second conducting layer may be formed from poly or any other conductive material. At least a portion of the diaphragm layer may contact the second conducting layer such that the second conducting layer forms an electrical contact with the diaphragm layer.

At **324**, the diaphragm layer is released, thereby forming a diaphragm suspended on the substrate. For example, releasing the diaphragm may comprise etching through each of the substrate, the first structural layer and the second structural layer. Expanding further, a back side etch may be performed to etch the substrate so as to define an opening therethrough so as to release the diaphragm from the substrate side. In particular embodiments, the substrate may include a thin oxide (e.g., SiO_2) layer disposed on a first surface thereof facing the diaphragm. For example, the oxide layer may be deposited or grown on the substrate before depositing the first structural layer or otherwise the back plate layer thereon. The oxide layer may serve as an etch stop for the back side substrate etch.

The back side etch may be continued or another back side etch may subsequently be performed through the apertures defined in the back plate layer to remove the first structural layer and the second structural layer and release the diaphragm. In other embodiments, the back plate layer may be disposed above the diaphragm such that the diaphragm is disposed between the substrate and the back plate. In such embodiments, the subsequent etch may include a front side etch performed through the apertures defined in the back plate.

In various embodiments, releasing the diaphragm also releases the back plate layer, thereby forming a back plate suspended over the substrate above or below the diaphragm. In some embodiments, etching of the first and second structural layers may be performed for a predetermined time such that a portion of the first structural layer and a portion of the second structural layer proximate to the upward facing corrugations or downward facing corrugations of the diaphragm layer is not removed so as to form a perimetral (also referred to as "peripheral") support structure (e.g., as shown in FIG. **5**E). The portions of the first structural layer and/or the second structural layer may facilitate rounding of the corners and edges of the upward or downward facing corrugations formed in the diaphragm. In some embodiments, an inner radial edge of the portion of the second structural layer is positioned closer to the downward facing corrugation or upward facing corrugation defined in the diaphragm layer relative to an inner radial edge of the portion of the first structural layer. In other words, an inner sidewall of the portions of the first and second structural layers may be tapered from a first edge thereof proximate to the substrate towards a second edge proximate to the diaphragm layer such that the second edge is radially closer to the downward or upward facing corrugations relative to the first edge.

In some embodiments, the diaphragm formed using the method **300** may have a compliance which is at least two times more than a compliance of a similar constrained diaphragm that does not include the corrugations. Furthermore, the diaphragm may be able to withstand a pressure differential in between a range of 50 to 70 psi. While not shown, in some embodiments, the method **300** may also include forming a piercing or through-hole through the diaphragm and optionally, the back plate, for example to allow pressure equalization between a front volume and a back volume of the acoustic transducer formed using the method **300**.

FIGS. **4**A-**4**C illustrate process flows **400***a/b* for forming acoustic transducers **40***a* and **40***b* having downward and upward facing corrugations, respectively, according to an embodiment. The process **400***a/b* include providing a substrate **402***a/b* (e.g., a glass, Pyrex, quartz, silicon, silicon oxide or any other suitable substrate), at operation **1***a/b*.

At operation **2***a/b* a back plate layer **403***a/b* is deposited on the substrate **402***a/b* and a first conducting layer **416***a/b* is deposited on the back plate layer **403***a/b*. In some embodiments, the back plate layer **403***a/b* may include, for example, a LSN layer, and the first conducting layer **416***a/b* may include a conducting material (e.g., poly). At operation **3***a/b*, a plurality of apertures **417***a/b* are defined in the back plate layer **403***a/b* and the first conducting layer **416***a/b*, for example, using a wet or dry etching process. At operation **4***a/b*, the first conducting layer is selectively etched to form an electrical contact on the back plate layer **403***a/b*.

At operation **5***a/b*, a first structural layer **406***a/b*, for example, a first PSG or BPSG layer is deposited on the back plate layer **403***a/b*. The first structural layer **406***a/b* may be planarized (e.g., via CMP) after deposition on the back plate layer **403***a/b*. The first structural layer **406***a/b* may have an impurity content, for example, a first phosphorus content in a range between 2% and 5%. At operation **6***a* one or more enclosed trenches **407***a* are etched in the first structural layer **406***a* to serve as templates for forming downward facing corrugations in a diaphragm. In contrast, the first structural layer **406***b* is etched so as to form one or more enclosed pillars **407***b* from the first structural layer **406***b* to serve as templates for forming upward facing corrugations in a diaphragm. In particular embodiments, a wet etch process may be used etch the first structural layer **406***a/b* up to the back plate layer **403***a/b* disposed therebeneath, the back plate layer **403***a/b* serving as an etch stop for the wet etch.

At operation **7***a/b*, a second structural layer **408***a/b*, for example, a second PSG or BPSG layer having a second impurity content, for example, a second phosphorus content larger than the first impurity content so as to have a lower glass transition temperature than the first structural layer **406***a/b* is deposited on the first structural layer **406***a/b* and the open areas of the back plate layer **403***a/b*. The second structural layer **408***a/b* is conformally deposited on the first structural layer **406***a/b* so as to include one or more depressions **409***a* corresponding to the one or more enclosed trenches **407***a* formed in the first structural layer **406***a*, or one or more bumps **409***b* corresponding to the one or more enclosed pillars **407***b* formed from the first structural layer **406***b*. The enclosed trenches **407***a* or the enclosed pillars **407***b* may have sharp corners, as previously described herein.

At operation **8***a/b*, the second structural layer **408***a/b* is heated to a temperature above a glass transition temperature of the second structural layer **408***a/b*. This causes the second structural layer **408***a/b* to reflow which smooths or rounds the sharp edges and corners of depressions **409***a* and the bumps **409***b* formed in the second structural layer **408***a/b*.

At operation **9***a/b* a second conducting layer **418***a/b* (e.g., a poly layer) is deposited on the second structural layer **408***a/b* and patterned. At operation **10***a/b*, each of the second structural layer **408***a/b* and the first structural layer **406***a/b* are etched along the edges of each layers up to the back plate layer **403***a/b* so as to provide space for sealing a diaphragm layer **410***a/b* to the back plate layer **403***a/b*.

At operation **11***a/b*, the diaphragm layer **410***a/b* (e.g., a LSN layer) is deposited on the second structural layer **408***a/b* such that the diaphragm layer **410***a* includes one or more downward facing corrugations **412***a* corresponding to the one or more depressions **409***a* formed in the second structural layer **408***a*, or one or more upward facing corrugations **412***b* corresponding to the one or more bumps **409***b* formed in the second structural layer **408***b*. Furthermore, the diaphragm layer **410***a/b* contacts the back plate layer **403***a/b* so as to seal the edges of the acoustic transducer **40***a/b*. At operation **12***a/b*, a portion of the substrate **402***a/b*, and a bulk of the first structural layer **406***a/b* and the second structural layer **408***a/b* are etched (e.g., through the apertures **417***a/b* defined in the back plate layer **403***a/b*) so as to release the diaphragm layer **410***a/b* as well as the back plate layer **403***a/b*, thereby forming a diaphragm and back plate of the acoustic transducer **40***a/b*.

While operations of the method **400***a/b* result in the back plate **416***a/b* being disposed below the diaphragm **410***a/b*, in other embodiments, a back plate may be disposed above a diaphragm that includes corrugations (e.g., the diaphragm **410***a/b*). In such embodiments, a second structural layer is deposited on the diaphragm layer (e.g., the diaphragm layer **410***a/b*). A back plate layer is deposited on the second structural layer; and plurality of apertures are formed (e.g., etched) in the back plate layer. The apertures enable an etchant used to release the diaphragm layer to pass through the back plate and etch the second structural layer such that releasing the diaphragm also releases the back plate layer, thereby forming a back plate suspended on the substrate (e.g., the substrate **402***a/b*) over the diaphragm.

FIGS. **5**A-**5**D illustrate process flows **500***a/b* for forming acoustic transducers **50***a* and **50***b* having downward and upward facing corrugations, respectively, according to an embodiment. The process **500***a/b* include providing a substrate **502***a/b* (e.g., a glass, Pyrex, quartz, silicon, silicon oxide or any other suitable substrate), at operation **1***a/b*.

At operation **2***a/b*, a back plate layer **503***a/b* is deposited on the substrate **502***a/b* and a first conducting layer **516***a/b* is deposited on the back plate layer **503***a/b*. In some embodiments, the back plate layer **503***a/b* may include, for example, a LSN layer, and the first conducting layer **516***a/b* may include a conducting material (e.g., poly). At operation **3***a/b*, a plurality of apertures **517***a/b* are defined in the back plate layer **503***a/b* and the first conducting layer **516***a/b*, for example, using a wet or dry etching process. The apertures **517***a/b* may have any suitable shape, for example, square, rectangular, circular, oval, oblong, polygonal, etc. In particular embodiments, the apertures **517***a/b* may have a hexagonal shape with rounded corners. For example, FIG. **6** shows a top view of a portion of the back plate layer **503***a/b* having hexagonal apertures **517***a/b* defined therein. In particular embodiments, the hexagonal apertures **517***a/b* may have a width W between parallel sides thereof in a range between 10 and 20 microns (e.g., 10, 12, 14, 16, 18 and 20 microns inclusive of all ranges and values therebetween) and a pitch of 10-30 microns (e.g., 10, 15, 25 or 30 microns inclusive of all ranges and values therebetween).

At operation **4***a/b*, the first conducting layer **516***a/b* is selectively etched to form an electrical contact on the back plate layer **503***a/b*. At operation **5***a/b*, a first structural layer **506***a/b* is deposited on the substrate **502***a/b*. The first structural layer **506***a/b* may include a PSG or BPSG layer have a first impurity content, for example, a first phosphorus content in a range between 4% and 10%. In some embodiment, the first structural layer **506***a/b* may be planarized (e.g., via CMP) after deposition on the back plate layer **503***a/b*.

At operation **6***a*, enclosed trenches **507***a* are formed in the first structural layer **506***a* to serve as templates for forming downward facing corrugations in a diaphragm. In contrast, in operation **6***b*, the first structural layer **506***b* is etched so as to form enclosed pillars **507***b* from the first structural layer **506***b* which serve as templates for a upward facing corrugations to be formed in a diaphragm. In particular embodiments, the first structural layer **506***a/b* is etched using a timed dry etch process such that the dry etch does not reach the back plate layer **503***a/b* and portions of the first structural layer **506***a/b* remain disposed on the entire back plate layer **503***a/b*.

At operation **7***a/b*, the first structural layer **506***a/b* is heated to a temperature above a glass transition temperature of the first structural layer **506***a/b* so as to cause the first structural layer **506***a/b* to reflow and smoothen the edges or corners of the enclosed trenches **507***a* or enclosed pillars **507***b* defined in the first structural layer **506***a* and **506***b*, respectively. At operation **8***a/b*, a second structural layer **508***a/b*, for example, a second PSG or BPSG layer is deposited over the first structural layer **506***a/b*, such that the second structural layer **508***a/b* includes depressions **509***a* or bumps **509***b* corresponding to the enclosed trenches **507***a* or enclosed pillars **507***b*, respectively defined in the first structural layer **506***a/b*. The second structural layer **508***a/b* may have a second impurity content, for example, a second phosphorus content lower than the first impurity content (e.g., a first phosphorus content) of the first structural layer **506***a/b* (e.g., in a range between 2% and 6%), therefore having a glass transition temperature higher than the first structural layer **506***a/b*.

At operation **9***a/b*, the second structural layer **508***a/b* is heated to a temperature above the glass transition temperature thereof, so as to cause the second structural layer **508***a/b* to reflow, further rounding the corners of the depressions **509***a* and bumps **509***b*. At operation **10***a/b*, a second conducting layer **518***a/b* is deposited and patterned on the second structural layer **508***a/b*. At operation **11***a/b*, each of the second structural layer **508***a/b* and the first structural layer **506***a/b* are etched along the edges of each layers up to the back plate layer **503***a/b* so as to provide space for sealing a diaphragm layer **510***a/b* to the back plate layer **503***a/b*.

At operation **12***a/b*, a diaphragm layer **510***a/b* (e.g., a LSN layer) is deposited on the second structural layer **508***a/b* such that the diaphragm layer **510***a* includes one or more downward facing corrugations **512***a* corresponding to the one or more depressions **509***a* formed in the second structural layer **508***a*, or one or more upward facing corrugations **512***b* corresponding to the one or more bumps **509***b* formed in the second structural layer **508***b*. Furthermore, the diaphragm layer **510***a/b* contacts the back plate layer **503***a/b* at radial edges thereof, so as to seal the edges of the acoustic transducer **50***a/b*. At operation **13***a/b*, a portion of the substrate **502***a/b* is etched, and at operation **14***a/b*, a bulk of the first structural layer **506***a/b* and the second structural layer **508***a/b* is etched (e.g., through the apertures **517***a/b* defined in the back plate layer **503***a/b*) so as to release the diaphragm layer **510***a/b* as well as the back plate layer **503***a/b*, thereby forming a diaphragm and back plate of the acoustic transducer **50***a/b*.

FIG. **5**E shows an enlarged view of a portion of the acoustic transducer **50***a* indicated by the arrow A in FIG. **5**D operation **14***a*. As shown in FIG. **5**E, the first and second structural layers **506***a/b* and **508***a/b* are etched for a predetermined time such that a portion **522***a* of the first structural layer **506***a* and a portion **522***b* the second structural layer **508***b* proximate to perimetral edge of the diaphragm layer **510***a/b* and the downward facing corrugations **512***a* or upward facing corrugations **512***b* of the diaphragm layer **510***a* and **510***b*, respectively is not removed. The remaining portions **522***a* and **522***b* of the first and/or second structural layers **506***a/b* and **508***a/b* may facilitate rounding of the corners and edges of the downward or upward facing corrugations **512***a* and **512***b* formed in the diaphragm layer **510***a/b* by forming a perimetral support structure **522** for increasing strength and robustness of the diaphragm **510***a/b*. The portion **522***b* of the second structural layer **508***a* contacts the diaphragm layer **510***a*. Furthermore, an inner radial edge **524***b* of the portion **522***b* of the second structural layer **508***a* proximate to the diaphragm layer **510***a* is positioned radially closer to the downward facing corrugation **512***a* defined in the diaphragm layer **510***a* relative to an inner radial edge **524***a* of the portion **522***a* of the first structural layer **506***a* proximate to the substrate **502***a*. This may be due, for example, to the first structural layer **506***a* and the second structural layer **508***a* having different impurity contents (e.g., different phosphorus contents) which causes unequal etching, or due to proximity of the first structural layer **506***a* to an isotropic etch front.

FIG. **7**, panel A summarizes failing pressure of various representative sample wafer included in three wafer lots (lots A, B, and C) that include diaphragms having corrugations with sharp and degrees of smooth edges and formed using wet or dry etching. The diaphragms included in each of the wafer lots were tested by applying pressure to one side of the diaphragm until failure of the diaphragm.

Representative wafer **24** included in lot A includes a diaphragm having downward facing corrugations formed by etching a cavity in a PSG layer via dry etching. FIG. **7**, panel B is an SEM image of the representative sample wafer **24** of included in lot A. Focused Ion Beam (FIB) etching was used to section the wafer **24** so as to allow imaging of a cross-section of the diaphragm included in the wafer **24**. The diaphragms included in lot A wafer **24** failed at a pressure of about 9 psi.

Representative wafer **5** included in lot B includes a diaphragm having downward facing corrugations formed by etching a cavity in a PSG layer via a wet etch process. The corrugations have a depth at a center of the diaphragm of about 4.00 μm and at the edges of about 4.45 μm, and include rounded corners. FIG. **7**, panel C is an SEM image of lot B wafer **5**. The diaphragms included in the wafer **5** failed at a pressure of about 18 psi.

Representative wafer **15** included in lot B includes corrugations having a depth at a center of the diaphragm of about 4.45 μm and at the edges of about 4.83 μm, and includes rounded corners. FIG. **7**, panel D is an SEM image of the representative sample wafer **15**. The diaphragms included in lot B wafer **15** failed at a pressure of about 34 psi.

Representative wafer **25** included in lot C which was formed using dry etching, includes corrugations having a depth at a center of the diaphragm of about 3.66 μm and at the edges of about 3.32 μm, and includes rounded corners. Corrugation depth is shallowest among the group of wafers in FIG. **7**, panel A. While etching corrugations, unetched PSG was intentionally left at the bottom resulting in the smoothest corners after PSG reflow as described in relation to operation **6***a/b* and **7***a/b* of FIG. **5**B. FIG. **7**, panel E is an SEM image of the representative sample wafer **25** lot C. The diaphragms included in the wafer **25** failed at a pressure of about 60 psi. FIG. **8** is a scatter plot of diaphragm failures of various diaphragms formed using the methods described herein, showing that the smoothing the corrugations increases the failure strength of the diaphragms.

FIGS. **9**A-**9**C illustrate a process flows **600***a/b* for forming acoustic transducers **60***a* and **60***b* having downward and upward facing corrugations, respectively, according to an embodiment. The process **600***a/b* includes providing a substrate **602***a/b* (e.g., a glass, Pyrex, quartz, silicon, silicon oxide or any other suitable substrate), at operation **1***a/b*. At operation **2***a*, one or more enclosed trenches **605***a* are etched in the substrate using a wet or dry etch. In contrast, enclosed pillars **605***b* are formed in the substrate **602***b* at operation **2***b* (e.g., using a wet or a dry etch process). The one or more enclosed trenches **605***a* or pillars **605***b* may have sharp corners and edges, as previously described herein.

At operation **3***a/b* a first structural layer **608***a/b*, for example, a first PSG or BPSG layer having a first impurity content, for example, a first phosphorus content is deposited on the substrate **602***a/b*. The first structural layer **608***a/b* may be conformally deposited on the substrate **602***a/b* such that the first structural layer **608***a/b* includes depressions **609***a* and bumps **609***b* corresponding to the enclosed trenches **605***a* or the pillars **605***b*, respectively. Furthermore, the one or more depressions **609***a* and bumps **609***b* may have sharp corners and edges corresponding to the sharp corners and edges of the enclosed trenches **605***a* and the pillars **605***b*.

At operation **4***a/b*, the first structural layer **608***a/b* is heated to a temperature above a glass transition temperature thereof, causing the first structural layer **608***a/b* to reflow and smooth the corners and edges thereof, as previously described herein. At operation **5***a/b*, a diaphragm layer **610***a/b* is deposited on the first structural layer **608***a/b*, and a first conducting layer **618***a/b* (e.g., poly layer) is deposited on the diaphragm layer **610***a/b*. The diaphragm layer **610***a/b* is conformally deposited on the first structural layer such that the diaphragm layer **610***a* includes downward facing corrugations **612***a* corresponding to the depressions **609***a* formed in the first structural layer **608***a*, and the diaphragm layer **610***b* includes upward facing corrugations **612***b* corresponding to the bumps **609***b* formed in the first structural layer **608***b*, the upward and downward facing corrugations **612***a/b* including smooth or rounded corners and edges.

At operation **6***a/b*, the first conducting layer **618***a/b* is selectively etched so as to form an electrical contact on the diaphragm layer **610***a/b*. At operation **7***a/b*, a second structural layer **606***a/b* (e.g., an oxide layer, a second PSG or BPSG layer) is deposited on the diaphragm layer **610***a/b* and the first conducting layer **618***a/b*, and planarized (e.g., via chemical-mechanical polishing (CMP)). The second structural layer **606***a/b* may serve as a spacer to define a gap between the diaphragm layer **610***a/b* and a back plate layer.

At operation **8***a/b*, a second conducting layer **616***a/b* (e.g., a poly layer) is deposited on the second structural layer **606***a/b* and patterned to define an electrical contact for a back plate layer. At operation **9***a/b*, the structural layer **606***a/b* is etched along the edges thereof up to the diaphragm layer **610***a/b* so as to provide space for sealing a back plate layer to the diaphragm layer **610***a/b*.

At operation **10***a/b*, a back plate layer **603***a/b* (e.g., a LSN layer) is deposited on the second structural layer **606***a/b* and the second conducting layer **616***a/b*. The back plate layer **603***a/b* contacts the diaphragm layer **610***a/b* at edges of the acoustic transducer **60***a/b* to seal the acoustic transducer **60***a/b*. At operation **11***a/b*, apertures **617***a/b* are etched through the back plate layer **603***a/b* and the second conducting layer **616***a/b*. The apertures **617***a/b* may have any suitable shape, for example, square, rectangular, circular, oblong, oval, hexagonal, polygonal, any other suitable shape or a combination thereof.

At operation **12***a/b*, the substrate **602***a/b* is selectively etched up to the first PSG layer **606***a/b* to define a channel therein. At operation **13***a/b*, the first structural layer **608***b* is etched so as to release the diaphragm layer **610***a/b* from a first side. A portion of the first structural layer **608***a/b* disposed on the remaining portion of the substrate **602***a/b* is left un-etched and may serve as a support structure for the diaphragm layer **610***a/b*. Furthermore, the second structural layer **606***a/b* (e.g., a second PSG layer) is etched through the apertures **617***a/b* so as to release the diaphragm layer **610***a/b* from a second side opposite the first side, thereby forming the acoustic transducer **60***a/b* having a diaphragm **610***a/b* suspended over an opening in the substrate **602***a/b*. Etching of the structural layer **606***a/b* also releases the back plate layer **603***a/b*. A portion of the structural layer **606***a/b* proximate to corrugations **612***a/b* at the edges of the diaphragm layer is left un-etched and may facilitate smoothing of the corrugations **612***a/b* formed in the diaphragm layer **610***a/b* and/or increase a strength of the diaphragm layer **610***a/b*.

FIG. **10** is a schematic flow diagram of another method **700** for forming an acoustic transducer (e.g., the acoustic transducer **60**) including a diaphragm having upward facing corrugations or downward facing corrugations with smooth corners and edges formed therein, according to an embodiment. The acoustic transducer may include, for example, a MEMS acoustic transducer for use in a MEMS microphone assembly or a MEMS pressure sensor, and may be configured to generate electrical signals in response to acoustic signals or atmospheric pressure changes.

The method **700** includes providing a substrate, at **702**. The substrate may be formed from silicon, silicon oxide, glass, Pyrex, quartz, ceramics, or any other suitable material, and may include the substrate **602** described in detail with respect to the process **600**. At **704**, the substrate is selectively etched to form at least one of one or more enclosed trenches or enclosed pillars on the substrate. For example, the substrate may be etched using a wet etch or dry etch process to define the enclosed trenches or pillars on the substrate. At **706**, a first structural layer (e.g., the first PSG layer **608**) having a first impurity content is deposited on the substrate. In some embodiments, the first structural layer may include a PSG or BPSG. Furthermore, the impurity may include phosphorus such that a first phosphorus content of the first structural layer may be greater than 2% (e.g., in a range between 2% to 10%). The first structural layer is conformally deposited on the substrate such that the first structural layer includes one or more depressions or bumps defined thereon corresponding to the one or more enclosed trenches or pillars, respectively formed in the substrate.

At **708**, the first structural layer is heated to a temperature above a glass transition temperature of the first structural layer causing the first structural layer to reflow. As described previously herein, the cavities or pillars formed in the substrate may have sharp corners and edges (e.g., having a radius of curvature of less than 1 μm) such that the depressions or bumps formed in the first structural layer may have corresponding sharp corners and edges. Reflowing the first structural layer smoothens or rounds the corners and edges of the depressions or bumps formed in the first structural layer such that the corners and edges of the first structural layer may have a radius of curvature greater than 1 μm and less than 50 μm.

At **710**, a diaphragm layer (e.g., the diaphragm layer **610**) is deposited on the first structural layer such that the diaphragm layer includes at least one of downward facing corrugations corresponding to the depressions or upward facing corrugations corresponding to the bumps formed in the first structural layer. For example, a low stress material, for example LSN or a low stress ceramic may be deposited on the first structural layer (e.g., via a physical or chemical vapor deposition process). In other embodiments, the diaphragm layer may include a dielectric or conductive material (e.g., silicon oxide, silicon nitride, silicon carbide, gold, aluminum, platinum, etc.). Furthermore, the one or more downward facing corrugations or upward facing corrugations defined in the diaphragm layer have corners with radius of curvature corresponding to the second radius of curvature, i.e. radius of curvature after reflowing the first structural layer. In this manner, the stress concentration is reduced at the edges or corners of the corrugations increasing robustness and shock resistance.

In some embodiments, the method **700** also includes depositing a first conducting layer (e.g., the first conducting layer **618**) on the diaphragm layer, at **712**. In some embodiments, the first conducting layer may be formed from polysilicon (poly). In other embodiments, the first conducting layer may be formed from metals, doped silicon or any other suitable material. At **714**, the first conducting layer is patterned so as to form an electrical contact on the diaphragm layer.

In some embodiments, the method **700** also includes depositing a second structural layer which may include, for example, a second PSG or BPSG layer (e.g., the second PSG layer **606**) on the diaphragm layer, at **716**. The second structural layer may have a second impurity content, e.g., a second phosphorus content in a range between 2% and 10%, which may be the same or different (e.g., higher or lower) than the first phosphorus content included in the first structural layer. In other embodiments, the second structural layer may include an oxide, a nitride or any other suitable layer serving as a gap layer or spacer between the diaphragm layer and a back plate layer. In some embodiments, the second structural layer may be planarized, for example, via a chemical-mechanical planarization (CMP) process.

In some embodiments, a back plate layer (e.g., the back plate layer **603**) may be deposited on the second structural layer, at **720**. The back plate layer may be formed from a low stress material, for example low stress silicon nitride (LSN), low stress oxide or any other suitable material. The back plate layer may be deposited using PVD, LPCVD, PECVD, ALD, any other suitable process or a combination thereof. The back plate layer may be relatively inflexible relative to a diaphragm to be formed from the diaphragm layer. A plurality of apertures may be formed in the back plate layer, at **722** as previously described with respect to the method **300**.

In some embodiments, the method **700** may also include depositing and patterning a second conducting layer (e.g., the second conducting layer **616**) before depositing the back plate layer on the structural layer, at **718**. In some embodiments, the first conducting layer may be formed from polysilicon (poly). In other embodiments, the first conducting layer may be formed from metals, doped silicon or any other suitable material. The first conducting layer may be deposited using PVD, thermal evaporation, e-beam evaporation, CVD, LPCVD, PECVD, ALD, or any other suitable process or a combination thereof. In other embodiments, the second conducting layer may be deposited on the back plate layer. The second conducting layer contacts the back plate layer and forms an electrical contact therewith. Furthermore, forming the plurality of apertures also forms corresponding apertures through the second conducting layer.

At **724**, the diaphragm layer is released, thereby forming a diaphragm suspended over the substrate. In some embodiments, releasing the diaphragm may include etching through each of the substrate and the first structural layer to release the diaphragm from a first side (e.g., a back side of the acoustic transducer). Furthermore, the second structural layer (e.g., a second PSG layer) may be etched through the apertures so as to also release the diaphragm from a second side opposite the first side. The etching may also release the back plate layer so as to form a back plate suspended over the first diaphragm. In particular embodiments, the etching is performed for a predetermined time such that a portion of the second structural layer proximate to the upward facing corrugations or downward facing corrugations of the diaphragm layer is not removed. The portion of the second structural layer may facilitate rounding of the corners and edges of the upward or downward facing corrugations formed in the diaphragm.

In some embodiments, the diaphragm formed using the method **700** may have a compliance which is at least two times more than a compliance of a similar constrained diaphragm that does not include the corrugations. Furthermore, the diaphragm may be able to withstand a pressure differential in between a range of 50 to 70 psi. While not shown, in some embodiments, the method **700** may also include forming a piercing or through-hole through the diaphragm and optionally, the back plate, for example to allow pressure equalization between a front volume and a back volume of the acoustic transducer.

FIGS. **11**A-**11**C illustrate process flows **800***a/b* for forming acoustic transducers **80***a* and **80***b* having downward and upward facing corrugations, respectively, according to an embodiment. The process **800** is substantially similar to the process **500** but includes some differences highlighted herein. The process **800***a/b* include providing a substrate **802***a/b* (e.g., a glass, Pyrex, quartz, silicon, silicon oxide or any other suitable substrate), at operation **1***a/b*.

At operation **2***a/b* a back plate layer **803***a/b* is deposited on the substrate **802***a/b* and a first conducting layer **816***a/b* is deposited on the back plate layer **803***a/b*. At operation **3***a/b*, a plurality of apertures **817***a/b* are defined in the back plate layer **803***a/b* and the first conducting layer **816***a/b*, for example, using a wet or dry etching process. At operation **4***a/b*, the first conducting layer is selectively etched to form an electrical contact on the back plate layer **803***a/b*.

At operation **5***a/b*, a first structural layer **806***a/b* (e.g., a first PSG or BPSG layer) is deposited on the back plate layer **803***a/b*. The first structural layer **806***a/b* may be planarized (e.g., via CMP) after deposition on the back plate layer **803***a/b*. The first structural layer **806***a/b* may have a first impurity content, for example, a first phosphorus content in a range between 2% and 10%. At operation **6***a* one or more enclosed trenches **807***a* are etched in the first structural layer **806***a*, on operation **6***b* the first structural layer **806***b* is etched so as to form enclosed pillars **807***b* from the first structural layer **806***b*, as previously described herein with respect to FIGS. **4**A-**4**C. In particular embodiments, a wet etch process may be used etch the first structural layer **806***a/b* up to the back plate layer **803***a/b* disposed therebeneath, the back plate layer **803***a/b* serving as an etch stop for the wet etch.

At operation **7***a/b*, a second structural layer **808***a/b*, for example, a second PSG or BPSG layer is deposited on the first structural layer **806***a/b* and the open areas of the back plate layer **803***a/b*. Unlike the process **400** shown in FIGS. **4**A-**4**C, the second structural layer **808***a/b* has the same impurity content, for example, the same phosphorus content as the first structural layer **806***a/b* (e.g., in a range between 2% and 10%). The second structural layer **808***a/b* is conformally deposited on the first structural layer **806***a/b* so as to include one or more depressions **809***a* corresponding to the one or more enclosed trenches **807***a* formed in the first structural layer **806***a*, or one or more bumps **809***b* corresponding to the one or more enclosed pillars **807***b* formed from the first structural layer **806***b*. The cavities **809***a* or the pillars **809***b* may have corners which are rounder than the corners of the cavities **807***a* or pillars **807***b* of the underlying first structural layer **806***a/b*.

At operation **8***a/b*, the second structural layer **808***a/b* is heated to a temperature above a glass transition temperature of the second structural layer **808***a/b* and thereby, also the first structural layer **806***a* causing the second structural layer **808***a/b* and, in some implementations, also the first structural layer **806***a* to reflow. Reflowing further smooths or rounds the sharp edges and corners of depressions **809***a* and the bumps **809***b* formed in the second structural layer **808***a/b*.

At operation **9***a/b* a second conducting layer **818***a/b* (e.g., a poly layer) is deposited on the second structural layer **808***a/b* and patterned. At operation **10***a/b*, each of the second structural layer **808***a/b* and the first structural layer **806***a* are etched along the edges of each layers up to the back plate layer **803***a/b* so as to provide space for sealing a diaphragm layer **810***a/b* to the back plate layer **803***a/b*.

At operation **11***a/b*, the diaphragm layer **810***a/b* (e.g., a LSN layer) is deposited on the second structural layer **808***a/b* such that the diaphragm layer **810***a* includes one or more downward facing corrugations **812***a* corresponding to the one or more depressions **809***a* formed in the second structural layer **808***a*, or one or more upward facing corrugations **812***b* corresponding to the one or more bumps **809***b* formed in the second structural layer **808***b*. Furthermore, the diaphragm layer **810***a/b* contacts the back plate layer **803***a/b* so as to seal the edges of the acoustic transducer **80***a/b*. At operation **12***a/b*, a portion of the substrate **802***a/b*, and a bulk of the first structural layer **806***a* and the second structural layer **808***a/b* are etched (e.g., through the apertures **817***a/b* defined in the back plate layer **803***a/b*) so as to release the diaphragm layer **810***a/b* as well as the back plate layer **803***a/b*, thereby forming a diaphragm and back plate of the acoustic transducer **80***a/b*.

A small portion of the structural layers **806***a* and **808***a/b* are left un-etched near a perimeter or edge of the diaphragm layer, as shown in operations **12***a/b* to provide a perimetral support structure. Using structural layers **806***a* and **808***a/b* having the same impurity content may allow the etching to proceed at the same rate for each of the structural layers **806***a* and **808***a/b* and may yield a tapered profile for the remaining portion of the structural layers **806***a* and **808***a/b*. This is because etching of the structural layers **806***a* and **808***a/b* initiates from the apertures **817***a/b* defined in the back plate **803***a/b* and occurs isotropically. Therefore, the portions of the structural layers **806***a* and **808***a/b* farthest from the apertures **817***a/b* etch last. The remaining portion of the structural layers **806***a* and **808***a/b* may slope inwardly from the back plate layer **803***a/b* towards the diaphragm layer **810**_a/b_ and may serve to increase a strength of diaphragm layer **810**_a/b_ and/or facilitate rounding of the corrugations **812**_a/b_.

FIGS. **12**A-**12**D illustrate process flows **900**_a/b_ for forming acoustic transducers **90**_a_ and **90**_b_ having downward and upward facing corrugations, respectively, according to an embodiment. The process **900**_a/b_ is substantially similar to the process **500**_a/b_ with some differences highlighted herein.

The process **900**_a/b_ include providing a substrate **902**_a/b_ (e.g., a glass, Pyrex, quartz, silicon, silicon oxide or any other suitable substrate), at operation **1**_a/b_. At operation **2**_a/b_, a back plate layer **903**_a/b_ is deposited on the substrate **902**_a/b_ and a first conducting layer **916**_a/b_ is deposited on the back plate layer **903**_a/b_. At operation **3**_a/b_, a plurality of apertures **917**_a/b_ are defined in the back plate layer **903**_a/b_ and the first conducting layer **916**_a/b_, for example, using a wet or dry etching process.

At operation **4**_a/b_, the first conducting layer **916**_a/b_ is selectively etched to form an electrical contact on the back plate layer **903**_a/b_. At operation **5**_a/b_, a first structural layer **906**_a/b_, for example, a first PSG or BPSG layer is deposited on the substrate **902**_a/b_. The first PSG layer **906**_a/b_ may have a first impurity content, for example, a first phosphorus content, in a range between 2% and 10%. In some embodiment, the first structural layer **906**_a/b_ may be planarized (e.g., via CMP) after deposition on the back plate layer **903**_a/b_.

At operation **6**_a_, one or more enclosed trenches **907**_a_ are formed in the first structural layer **906**_a_, or, the first structural layer **906**_b_ is etched so as to form one or more enclosed pillars **907**_b_. In particular embodiments, the first structural layer **906**_a/b_ is etched using a timed dry etch process such that the dry etch does not reach the back plate layer **903**_a/b_ and portions of the first structural layer **906**_a/b_ remain disposed on the entire back plate layer **903**_a/b_.

At operation **7**_a/b_, the first structural layer **906**_a/b_ is heated to a temperature above a glass transition temperature thereof so as to cause the first structural layer **906**_a/b_ to reflow and smoothen the edges or corners of the enclosed trenches **907**_a_ or pillars **907**_b_ defined in the first structural layer **906**_a_ and **906**_b_, respectively. At operation **8**_a/b_ a second structural layer **908**_a/b_, for example, a second PSG or BPSG layer, is deposited over the first structural layer **906**_a/b_, such that the second structural layer **908**_a/b_ includes depressions **909**_a_ or bumps **909**_b_ corresponding to the enclosed trenches **907**_a_ or pillars **907**_b_, respectively defined in the first structural layer **906**_a/b_. Edges or corners of the depressions **909**_a_ or bumps **909**_b_ may be smoother or rounder than the corresponding enclosed trenches **907**_a_ and pillars **907**_b_. Different from process **500**_a/b_, the second structural layer **908**_a/b_ may have a second impurity content, for example, a second phosphorus content, equal to the first impurity content (e.g., in a range between 2% and 10%). For example, the second structural layer **908**_a/b_ may include the same materials as the first structural layer **906**_a/b_

At operation **9**_a/b_ the second structural layer **908**_a/b_ is heated to a temperature above the glass transition temperature thereof, so as to cause the second structural layer **908**_a/b_, and in some implementations, also the first structural layer to reflow, further rounding the corners of the depressions **909**_a_ and bumps **909**_b_. At operation **10**_a/b_, a second conducting layer **918**_a/b_ is deposited and patterned on the second structural layer **908**_a/b_. Also shown in operation **10**_a/b_, each of the second structural layer **908**_a/b_ and the first structural layer **906**_a/b_ are etched along the edges of each layers up to the back plate layer **903**_a/b_ so as to provide space for sealing a diaphragm layer **910**_a/b_ to the back plate layer **903**_a/b_.

At operation **11**_a/b_, the diaphragm layer **910**_a/b_ (e.g., a LSN layer) is deposited on the second structural layer **908**_a/b_ such that the diaphragm layer **910**_a_ includes one or more downward facing corrugations **912**_a_ corresponding to the one or more depressions **909**_a_ formed in the second structural layer **908**_a_, or one or more upward facing corrugations **912**_b_ corresponding to the one or more bumps **909**_b_ formed in the second structural layer **908**_b_. Furthermore, the diaphragm layer **910**_a/b_ contacts the back plate layer **903**_a/b_ at radial edges thereof, so as to seal the edges of the acoustic transducer **90**_a/b_. At operation **12**_a/b_, a portion of the substrate **902**_a/b_ is etched, and at operation **13**_a/b_, a bulk of the first structural layer **906**_a/b_ and the second structural layer **908**_a/b_ is etched (e.g., through the apertures **917**_a/b_ defined in the back plate layer **903**_a/b_) so as to release the diaphragm layer **910**_a/b_ as well as the back plate layer **903**_a/b_, thereby forming a diaphragm and back plate of the acoustic transducer **90**_a/b_. A small portion of the structural layers **906**_a/b_ and **908**_a/b_ are left un-etched near perimeter or edge of the diaphragm layer, as shown in operations **13**_a/b_ to from a perimetral support structure. The remaining portion of the structural layers **906**_a/b_ and **908**_a/b_ may taper inwardly from the back plate layer **903**_a/b_ towards the diaphragm layer **910**_a/b_ and may serve to increase a strength of diaphragm layer **910**_a/b_ and/or facilitate rounding of the corrugations **912**_a/b_.

FIGS. **13**A-**13**E illustrate a process flow **1000** for forming an acoustic transducer having downward and upward facing corrugations, according to an embodiment. In particular, the process flow **1000** can be utilized to form a dual diaphragm acoustic transducer **100** (shown in FIG. **13**E) including downward and upward corrugations. The process **1000** includes providing a substrate **1002** (e.g., a glass, Pyrex, quartz, silicon, silicon oxide or any other suitable substrate), at operation **1**. At operation **2**, one or more enclosed trenches **1005** are etched in the substrate using a wet or dry etch. The one or more enclosed trenches **1005** may have sharp corners and edges, as previously described herein.

At operation **3**, a first structural layer **1008**, for example, a first PSG or BPSG layer having a first impurity content, for example, a first phosphorous content is deposited on the substrate **1002**. The first structural layer **1008** may be conformally deposited on the substrate **1002** such that the first structural layer **1008** includes depressions **1009** corresponding to the enclosed trenches **1005**. Furthermore, the one or more depressions **1009** may have sharp corners and edges corresponding to sharp corners and edges of the enclosed trenches **1005**.

At operation **4**, the first structural layer **1008** is heated to a temperature above a glass transition temperature thereof, causing the first structural layer **1008** to reflow and smooth the corners and edges thereof, as previously described herein. At operation **5**, a first diaphragm layer **1010** is deposited on the first structural layer **1008**, and a first conducting layer **1018** (e.g., poly layer) is deposited on the first diaphragm layer **1010**. The first diaphragm layer **1010** is conformally deposited on the first structural layer such that the first diaphragm layer **1010** includes downward facing corrugations **1012** corresponding to the depressions **1009** formed in the first structural layer **1008**. The downward facing corrugations **1012** can include smooth or rounded corners and edges.

At operation **6**, the first conducting layer **1018** is selectively etched so as to form an electrical contact on the first diaphragm layer **1010**. At operation **7**, a second structural layer **1006** (e.g., an oxide layer, a second PSG or BPSG layer) is deposited on the first diaphragm layer **1010** and the first conducting layer **1018**, and planarized (e.g., via chemical-mechanical polishing (CMP)). The second structural layer **1006** may serve as a spacer to define a gap between the diaphragm layer **1010** and a back plate layer.

At operation **8**, the second structural layer **1006** is etched along the edges thereof up to first diaphragm layer **1010** so as to provide space for a sealing a back plate layer to the first diaphragm layer **1010**. At operation **9**, a back plate layer **1016** is deposited and patterned on the second structural layer **1006**. The back plate layer **1016** can include one or more layers of poly and silicon nitride. For example, the back plate layer **1016** can include a silicon nitride layer between two poly layers. The back plate layer **1016** is patterned to form back plate apertures that can allow posts in a second diaphragm to pass through (discussed further below).

At operation **10**, a third structural layer **1014** is deposited over the back plate layer **1016**. In some embodiments, the third structural layer **1014** can be similar in composition to the first and the second structural layers **1008** and **1006** discussed above. At operation **11**, the third structural layer **1014** is patterned to form pillars **1024**, which aid in forming corrugations in a second diaphragm, discussed further below. At operation **12**, a fourth structural layer **1020** for supporting the second diaphragm is deposited and may form a portion of a peripheral support structure. In some embodiments, the fourth structural layer **1020** can include one or more layers. For example, the fourth structural layer **1020** can include multiple layers of PSG or BPSG with different concentration levels. As an example the fourth structural layer **1020** can include two sub-layers of PSG or BPSG, a first with a concentration of 5%-9% and another with a concentration of 2.5%-6.5%. In some embodiments, the sub-layers can be deposited over one another with increasing concentrations. In some embodiments, a middle sub-layer can be sandwiched between two sub-layers having concentrations that are less than that of the middle layer. The fourth structural layer **1020** can be conformally deposited over the pillars **1024** formed using the third structural layer **1014**, resulting in fourth structural layer pillars **1022**. At least a portion of the fourth structural layer **1020** makes contact with the back plate layer

At operation **13**, a second conducting layer **1026** is deposited and patterned over the fourth structural layer **1020**. The second conducting layer **1026** can be of similar material to the first conducting layer **1018**, and can be patterned in some portions to form apertures therethrough. At least some apertures in the second conducting layer **1026** can be aligned with apertures in the back plate layer **1016**. At operation **14**, the fourth structural layer **1020**, the second structural layer **1006** are patterned to expose the first conducting layer **1018** or first diaphragm layer **1010**. In particular, the fourth and the second structural layers **1020** and **1006** can be etched primarily in regions that do not have the second conducting layer **1026** deposited over the fourth structural layer **1020** and the back plate layer **1016** deposited over the second structural layer **1006**, and that lie above the first conductive layer **1018**. However, the portions of the fourth structural layer **1020** forming the fourth structural layer pillars **1022** are retained. The etching of the fourth structural layer **1020** and the second structural layer **1006** can form one or more cavities **1028** that are defined, at least in part, by the apertures in the back plate layer **1016** and the apertures in the second conducting layer **1026**. As discussed further below, the cavities **1028** can be used to form posts of the second diaphragm.

At operation **15**, a spacer layer **1030** can be deposited and patterned subsequent to the patterning of the fourth structural layer **1020** and the second structural layer **1006** to from the cavities **1028**. The spacer layer **1030** can be formed using silicon oxide, and can be deposited conformally over the fourth structural layer **1020**, the second conducting layer **1026**, the exposed portions of the first conducting layer **1018** within the cavities **1028**, and the fourth structural layer pillars **1022**. The spacer layer **1030** can be patterned to form apertures **1032** that expose portions of the underlying second conducting layer **1026** and the first conducting layer **1018**. The spacer layer **1030** can allow the formation of a gap between portions of posts of the second diaphragm and the first conducting layer **1018** of the first diaphragm layer **1008**. The thickness of the spacer layer can be based on the desired magnitude of the gap. In some embodiments, where no gap is desired the spacer layer **1030** may not be deposited.

At operation **16**, a second diaphragm layer **1034** is deposited over the spacer layer **1030**, or if the spacer layer **1030** is not utilized, conformally over the fourth structural layer **1020**, the second conducting layer **1026**, the exposed portions of the first conducting layer **1018** within the cavities **1028**, and the fourth structural layer pillars **1022**. The second diaphragm layer **1034** can be similar to the first diaphragm layer **1010**. However, unlike the first diaphragm layer **1010**, which includes downward facing corrugations **1012**, the second diaphragm **1034** can include upward facing corrugations **1038** formed over the fourth structural layer pillars **1022**. The second diaphragm **1034** also may form at least one anchor post **1040** and at least two posts **1042** spaced apart from the anchor post **1040**. The anchor post **1040** includes an apex **1044** formed at the bottom of the cavity **1028** (operation **15**) and makes contact with and is coupled to the first conducting layer **1018**. The portions of the second diaphragm **1034** between the anchored post **1040** and the at least two posts **1042** make contact with and are coupled to the second conducting layer **1026**. The second diaphragm layer **1034** can be patterned to form a plurality of openings **1036** that can expose the underlying spacer layer **1030** or, in instances where no spacer layer **1030** is used, the underlying fourth structural layer **1020**.

At operation **17**, a portion of the apex **1044** (of the anchor post **1040**) of the second diaphragm **1034**, a portion of the first conducting layer **1018** under the apex **1044**, and a portion of the first diaphragm layer **1008** under the apex **1044** are patterned to form a pierce or a through hole **1046**. The through hole **1046** can allow pressure equalization between a front volume and a back volume of the acoustic transducer.

At operation **18**, portions of the second structural layer **1006** (between the first diaphragm **1010** and the back plate **1016**), portions of the fourth structural layer **1020** (between the back plate **1016** and the second diaphragm **1034**), and the third structural layer **1014** (e.g., pillars **1024**) are removed by an etchant. For example, an isotropic etchant (e.g., a wet etchant such as buffered hydrofluoric acid) can be allowed to flow through the openings **1036** formed in the second diaphragm **1034**. Removing portions of the fourth structural layer **1020** and the second structural layer **1006** result in internal cavities **1048** defined by the second diaphragm **1034** and the first diaphragm **1010**. However, the etching process can be controlled such that not all of the second structural layer **1006** and the fourth structural layer **1020** is removed. Instead, a peripheral support structure

1038 between the peripheries of the first diaphragm layer **1010** and the second diaphragm layer **1034** is retained. The peripheral support structure **1038** is positioned proximate to corrugations **1012** and **1038** and can increase the strength of the first diaphragm layer **1010** and the second diaphragm layer **1034**.

In some embodiments, the second structural layer **1006** and the fourth structural layer **1020** can have different concentrations of impurities, such as phosphorous or boron. For example, in some embodiments, the second structural layer **1006** can have a concentration of phosphorous between 2% and 6%, and the fourth structural layer **1020** can have a concentration of phosphorous between 4% and 10%. Varying the concentration of phosphorous, or other impurities, can allow a non-uniform etching of the second structural layer **1006** in relation of the fourth structural layer **1020**, resulting in a formation of a tapered peripheral support structure **1038**, which can improve the strength of the first and the second diaphragms **1010** and **1034**.

At operation **19**, a portion of the substrate **1002** and a bulk of the first structural layer **1008** are etched so as to release the first diaphragm layer **1010**, and to form the acoustic transducer **100**.

In some embodiments, a method of forming an acoustic transducer comprises providing a substrate, and depositing a first structural layer on the substrate. The first structural layer is selectively etched to form at least one of an enclosed trench or an enclosed pillar on the structural layer. A second structural layer is deposited on the structural layer. The second structural layer includes a depression or a bump corresponding to the enclosed trench or the enclosed pillar, respectively formed in the first structural layer. At least the second structural layer is heated to a temperature above a glass transition temperature of the second structural layer causing the second structural layer to reflow. A diaphragm layer is deposited on the second structural layer such that the diaphragm layer includes at least one of a downward facing corrugation corresponding to the depression or an upward facing corrugation corresponding to the bump formed in the second structural layer. The diaphragm layer is released, thereby forming a diaphragm suspended over the substrate.

In some embodiments, a method of forming an acoustic transducer comprises providing a substrate and selectively etching the substrate to form at least one of an enclosed trenches or an enclosed pillar on the substrate. A first structural layer is deposited on the substrate. The first structural layer includes at least one of a depression or a bump corresponding to the enclosed trenches or the enclosed pillar, respectively formed in the substrate. The first structural layer is heated to a temperature above a glass transition temperature of the first structural layer causing the first structural layer to reflow. A diaphragm layer is deposited on the first structural layer such that the diaphragm layer includes at least one of a downward facing corrugation corresponding to the depression or an upward facing corrugation corresponding to the bump formed in the first structural layer. The diaphragm layer is released, thereby forming a diaphragm suspended over the substrate.

In some embodiments, an acoustic transducer is formed by the process of providing a substrate, and depositing a first structural layer on the substrate. The first structural layer is selectively etched to form at least one of an enclosed trench or an enclosed pillar on the structural layer. A second structural layer is deposited on the structural layer. The second structural layer includes a depression or a bump corresponding to the enclosed trench or the enclosed pillar, respectively formed in the first structural layer. At least the second structural layer is heated to a temperature above a glass transition temperature of the second structural layer causing the second structural layer to reflow. A diaphragm layer is deposited on the second structural layer such that the diaphragm layer includes at least one of a downward facing corrugation corresponding to the depression or an upward facing corrugation corresponding to the bump formed in the second structural layer. The diaphragm layer is released, thereby forming a diaphragm suspended over the substrate.

In some embodiments, a method can include providing a substrate; depositing a first structural layer on the substrate; selectively etching the first structural layer to form at least one of an enclosed trench or enclosed pillar on the first structural layer; depositing a second structural layer on the first structural layer, the second structural layer including at least one of a depression or a bump corresponding to the at least one of the enclosed trench or the enclosed pillar formed in the first structural layer; heating at least the second structural layer to a temperature above a glass transition temperature of the second structural layer causing the second structural layer to reflow; depositing a diaphragm layer on the second structural layer such that the diaphragm layer includes at least one of a downward facing corrugation corresponding to the depression or an upward facing corrugation corresponding to the bump formed in the second structural layer; and releasing the diaphragm layer, thereby forming a diaphragm suspended over the substrate.

In some embodiments, at least one of the first structural layer or the second structural has an impurity content. In some embodiments, at least one of the first structural layer and the second structural layer comprises phosphosilicate glass (PSG) or borophosphosilicate glass (BPSG), and wherein an impurity content in at least one of the first structural layer or the second structural layer comprises phosphorus. In some embodiments, the first structural layer is a first PSG layer having a first phosphorus content, and the second structural layer is a second PSG layer having a second phosphorus content different from the first phosphorus content. In some embodiments, the first structural layer is a first PSG layer having a first phosphorus content, and the second structural layer is a second PSG layer having a second phosphorus content being equal to the first phosphorus content. In some embodiments, the second phosphorus content is greater than 2%. In some embodiments, the first phosphorus content is between 4% and 10% and the second phosphorus content is between 2% and 6%, the first phosphorus content being greater than the second phosphorus content. In some embodiments, the first phosphorus content is between 2% and 6%, and the second phosphorus content is between 4% and 10%, the second phosphorus content being greater than the first phosphorus content.

In some embodiments, the temperature during heating is greater than a glass transition temperature of the second PSG layer but lower than a glass transition temperature of the first PSG layer. In some embodiments, the temperature during heating is greater than a glass transition temperature of each of the first PSG layer and the second PSG layer. In some embodiments, the method further comprises before depositing the second PSG layer, heating the first PSG layer above a glass transition temperature of the first PSG layer so as to cause the first PSG layer to reflow. In some embodiments, the depression or the bump formed in the second structural layer prior to heating the second structural layer includes edges having a first radius of curvature of less than 1 mm, and wherein the depression or the bump, after heating the structural layer, includes edges having a second radius of curvature of greater than 1 μm and less than 50 μm such that each of the downward facing corrugations or the upward facing corrugation defined in the diaphragm layer has a radius of curvature corresponding to the second radius of curvature. In some embodiments, releasing the diaphragm comprises etching through each of the substrate, the first structural layer and the second structural layer; and wherein etching of the first structural layer and the second structural layer is performed such that a portion of the first structural layer and a portion of the second structural layer proximate to a perimetral edge of the diaphragm layer is not removed.

In some embodiments, the portion of the second structural layer contacts the diaphragm layer, and wherein an inner radial edge of the portion of the second structural layer proximate to the diaphragm is positioned radially closer to the downward facing corrugation or upward facing corrugation defined in the diaphragm layer relative to an inner radial edge of the portion of the first structural layer proximate to the substrate. In some embodiments, the method further comprises before depositing the first structural layer, depositing a back plate layer on the substrate; depositing a first conducting layer on the back plate layer; forming apertures through the back plate layer and the first conducting layer; and selectively etching the first conducting layer so as to form an electrical contact on the back plate layer; wherein the first structural layer is deposited on the first conducting layer, and wherein releasing the diaphragm layer also releases the back plate layer, thereby forming a back plate suspended on the substrate below the diaphragm.

In some embodiments, the first structural layer is selectively etched up to the back plate layer. In some embodiments, the first structural layer is selectively etched such that the etch process is stopped before reaching the back plate layer. In some embodiments, the method further comprises: before depositing a diaphragm layer on the second structural layer, depositing and patterning a second conducting layer on the second structural layer, wherein at least a portion of the diaphragm layer contacts the second conducting layer. In some embodiments, the method further comprising planarizing the first structural layer after depositing the first structural layer over the back plate layer and prior to selectively etching the first structural layer. In some embodiments, the method further comprises before releasing the diaphragm layer, depositing a third structural layer on the diaphragm layer; depositing a back plate layer on the third structural layer; and forming a plurality of apertures in the back plate layer, wherein releasing the diaphragm also releases the back plate layer, thereby forming a back plate suspended on the substrate above the diaphragm.

In some embodiments, an acoustic transducer can be formed by the process of providing a substrate. The process can further include depositing a first structural layer on the substrate. The process can also include selectively etching the first structural layer to form at least one of an enclosed trench or enclosed pillar on the first structural layer. The process can further include depositing a second structural layer on the first structural layer, the second structural layer including at least one of a depression or a bump corresponding to the at least one of the enclosed trench or the enclosed pillar formed in the first structural layer. The process can also include heating the second structural layer to a temperature above a glass transition temperature of the second structural layer causing the second structural layer to reflow. The process can further include depositing a diaphragm layer on the second structural layer such that the diaphragm layer includes at least one of a downward facing corrugation corresponding to the depression or an upward facing corrugation corresponding to the bump formed in the second structural layer. The process can also include releasing the diaphragm layer, thereby forming a diaphragm suspended over the substrate.

In some embodiments, at least one of the first structural layer or the second structural has an impurity content. In some embodiments, at least one of the first structural layer and the second structural layer comprises phosphosilicate glass (PSG) or borophosphosilicate glass (BPSG), and wherein the impurity comprises phosphorus. In some embodiments, the first structural layer is a first PSG layer having a first phosphorus content, and the second structural layer is a second PSG layer having a second phosphorus content different from the first phosphorus content. In some embodiments, the temperature during heating is higher than a glass transition temperature of the second PSG layer but lower than a glass transition temperature of the first PSG layer. In some embodiments, the temperature during heating is greater than a glass transition temperature of each of the first PSG layer and the second PSG layer. In some embodiments, the first structural layer is a first PSG layer having a first phosphorus content, and the second structural layer is a second PSG layer having a second phosphorus content being equal to the first phosphorus content. In some embodiments, the process further comprises, before depositing the second PSG layer, heating the first PSG layer above a glass transition temperature of the first PSG layer so as to cause the first PSG layer to reflow.

In some embodiments, the depression or the bump formed in the second structural layer includes edges having a first radius of curvature of less than 1 mm, and wherein reflowing the second structural layer causes the corners to have a second radius of curvature of greater than 1 μm and less than 50 μm such that each of the downward facing corrugations or the upward facing corrugation defined in the diaphragm layer has a radius of curvature corresponding to the second radius of curvature. In some embodiments, the process further comprises before depositing the first structural layer, depositing a back plate layer on the substrate. The process further comprises depositing a first conducting layer on the back plate layer. The process further comprises forming apertures through the back plate layer and the first conducting layer, and selectively etching the first conducting layer so as to form an electrical contact on the back plate layer. In some embodiments, releasing the diaphragm layer also releases the back plate layer, thereby forming a back plate suspended on the substrate below the diaphragm.

In some embodiments, the process further comprises before depositing a diaphragm layer on the second structural layer, depositing and patterning a second conducting layer on the second structural layer, where at least a portion of the diaphragm layer contacts the second conducting layer, the second conducting layer forming an electrical contact with the diaphragm layer.

In some embodiments, a method can include providing a substrate; selectively etching the substrate to form an enclosed trench on the substrate; depositing a first structural layer on the substrate, the first structural layer including a depression corresponding to the enclosed trench formed on the substrate; depositing a first diaphragm layer on the first structural layer such that the first diaphragm layer includes a downward facing corrugation corresponding to the depression; depositing a second structural layer over the first diaphragm layer; depositing a back plate layer over the second structural layer; depositing a third structural layer over the back plate, the third structural layer including an enclosed pillar; depositing a second diaphragm layer over the third structural layer such that the second diaphragm layer includes an upward facing corrugation corresponding to the enclosed pillar in the third structural layer; and releasing the first diaphragm layer and the second diaphragm layer.

In some embodiments, the method further comprises depositing the back plate layer over the second structural layer, the back plate layer including at least one aperture; selectively etching the third structural layer and the second structural layer to form at least one cavity that extends through the at least one aperture; and depositing the second diaphragm layer over the third structural layer such that the second diaphragm includes at least one post corresponding to the at least one cavity, the at least one post being coupled to the first diaphragm layer.

In some embodiments, the method further comprises forming a through hole through the second diaphragm layer and the first diaphragm layer at a portion of the at least one post. In some embodiments, the method further comprises etching at least a portion of the first structural layer and the second structural layer to form at least one internal cavity defined in part by the first diaphragm layer and the second diaphragm layer. In some embodiments, the method further comprises etching at least a portion of the first structural layer and the second structural layer to form a peripheral support structure positioned between the first diaphragm layer and the second diaphragm layer, and wherein the peripheral support structure is positioned along a periphery of the first diaphragm layer.

In some embodiments, at least one of the second structural layer and the third structural layer has an impurity content. In some embodiments, at least one of the second structural layer and the third structural layer comprises phosphosilicate glass (PSG) or borophosphosilicate glass (BPSG), and wherein the impurity content comprises phosphorus. In some embodiments, the second structural layer is a first PSG layer having a first phosphorus content, and the third structural layer is a second PSG layer having a second phosphorus content different from the first phosphorus content. In some embodiments, the first phosphorus content is between 2% and 6%, and the second phosphorus content is between 4% and 10%, the second phosphorus content being greater than the first phosphorus content.

In some embodiments, an acoustic transducer can be formed by the process of providing a substrate; selectively etching the substrate to form an enclosed trench on the substrate; depositing a first structural layer on the substrate, the first structural layer including a depression corresponding to the enclosed trench formed on the substrate; depositing a first diaphragm layer on the first structural layer such that the first diaphragm layer includes a downward facing corrugation corresponding to the depression; depositing a second structural layer over the first diaphragm layer; depositing a back plate layer over the second structural layer; depositing a third structural layer over the back plate, the third structural layer including an enclosed pillar; depositing a second diaphragm layer over the third structural layer such that the second diaphragm layer includes an upward facing corrugation corresponding to the enclosed pillar in the third structural layer; and releasing the first diaphragm layer and the second diaphragm layer.

In some embodiments, the process further comprises depositing the back plate layer over the second structural layer, the back plate layer including at least one aperture; selectively etching the third structural layer and the second structural layer to form at least one cavity that extends through the at least one aperture; and depositing the second diaphragm layer over the third structural layer such that the second diaphragm includes at least one post corresponding to the at least one cavity, the at least one post being coupled to the first diaphragm layer.

In some embodiments, the process further comprises forming a through hole through the second diaphragm layer and the first diaphragm layer at a portion of the at least one post. In some embodiments, the process further comprises etching at least a portion of the first structural layer and the second structural layer to form at least one internal cavity defined in part by the first diaphragm layer and the second diaphragm layer. In some embodiments, the process further comprises etching at least a portion of the first structural layer and the second structural layer to form a peripheral support structure positioned between the first diaphragm layer and the second diaphragm layer, and wherein the peripheral support structure is positioned along a periphery of the first diaphragm layer. In some embodiments, at least one of the second structural layer and the third structural layer has an impurity content. In some embodiments, at least one of the second structural layer and the third structural layer comprises phosphosilicate glass (PSG) or borophosphosilicate glass (BPSG), and wherein the impurity content comprises phosphorus. In some embodiments, the second structural layer is a first PSG layer having a first phosphorus content, and the third structural layer is a second PSG layer having a second phosphorus content different from the first phosphorus content. In some embodiments, the first phosphorus content is between 2% and 6%, and the second phosphorus content is between 4% and 10%, the second phosphorus content being greater than the first phosphorus content.

With respect to the use of substantially any plural and/or singular terms herein, those having skill in the art can translate from the plural to the singular and/or from the singular to the plural as is appropriate to the context and/or application. The various singular/plural permutations may be expressly set forth herein for sake of clarity.

It will be understood by those within the art that, in general, terms used herein, and especially in the appended claims (e.g., bodies of the appended claims) are generally intended as “open” terms (e.g., the term “including” should be interpreted as “including but not limited to,” the term “having” should be interpreted as “having at least,” the term “includes” should be interpreted as “includes but is not limited to,” etc.).

It will be further understood by those within the art that if a specific number of an introduced claim recitation is intended, such an intent will be explicitly recited in the claim, and in the absence of such recitation no such intent is present. For example, as an aid to understanding, the following appended claims may contain usage of the introductory phrases “at least one” and “one or more” to introduce claim recitations. However, the use of such phrases should not be construed to imply that the introduction of a claim recitation by the indefinite articles “a” or “an” limits any particular claim containing such introduced claim recitation to inventions containing only one such recitation, even when the same claim includes the introductory phrases “one or more” or “at least one” and indefinite articles such as “a” or “an” (e.g., “a” and/or “an” should typically be interpreted to mean “at least one” or “one or more”); the same holds true for the use of definite articles used to introduce claim recitations. In addition, even if a specific number of an introduced claim recitation is explicitly recited, those skilled in the art will recognize that such recitation should typically be interpreted to mean at least the recited number (e.g., the bare recitation of "two recitations," without other modifiers, typically means at least two recitations, or two or more recitations).

Furthermore, in those instances where a convention analogous to "at least one of A, B, and C, etc." is used, in general such a construction is intended in the sense one having skill in the art would understand the convention (e.g., "a system having at least one of A, B, and C" would include but not be limited to systems that have A alone, B alone, C alone, A and B together, A and C together, B and C together, and/or A, B, and C together, etc.). In those instances where a convention analogous to "at least one of A, B, or C, etc." is used, in general such a construction is intended in the sense one having skill in the art would understand the convention (e.g., "a system having at least one of A, B, or C" would include but not be limited to systems that have A alone, B alone, C alone, A and B together, A and C together, B and C together, and/or A, B, and C together, etc.). It will be further understood by those within the art that virtually any disjunctive word and/or phrase presenting two or more alternative terms, whether in the description, claims, or drawings, should be understood to contemplate the possibilities of including one of the terms, either of the terms, or both terms. For example, the phrase "A or B" will be understood to include the possibilities of "A" or "B" or "A and B." Further, unless otherwise noted, the use of the words "approximate," "about," "around," "substantially," etc., mean plus or minus ten percent.

The foregoing description of illustrative embodiments has been presented for purposes of illustration and of description. It is not intended to be exhaustive or limiting with respect to the precise form disclosed, and modifications and variations are possible in light of the above teachings or may be acquired from practice of the disclosed embodiments. It is intended that the scope of the invention be defined by the claims appended hereto and their equivalents.

What is claimed is:

1. A capacitive microelectromechanical systems (MEMS) die, comprising:

a substrate having a through-hole;

a diaphragm having an annular corrugation disposed between a substantially planar central portion and an outer portion, the substantially planar central portion having a conductive portion,

the annular corrugation defined by softened edges or corners at an interface between the annular corrugation and the central and outer portions of the diaphragm;

a back plate having a conductive portion,

the back plate and the diaphragm disposed in spaced-apart relation to form a capacitive structure located over the through-hole of, and supported by, the substrate,

wherein the annular corrugation extends in a direction toward the backplate and is spaced apart from the substrate, wherein the corrugation increases the compliance of the diaphragm.

2. The capacitive MEMS die of claim **1**, wherein:

the softened edges or corners are characterized by a radius of curvature greater than 1 μm and less than 50 μm, and

the corrugated diaphragm has reduced stress at locations formed by the softened edges or corners.

3. The capacitive MEMS die of claim **1**, wherein at least a portion of the annular corrugation is located radially outwardly of the through-hole.

4. The capacitive MEMS die of claim **1**, wherein the annular corrugation is located radially outwardly of the through-hole.

5. The capacitive MEMS die of claim **1**, wherein the conductive portion of the diaphragm and the conductive portion of the back plate are substantially aligned and positioned over the through-hole.

6. The capacitive MEMS die of claim **1**, further comprising a structural layer supporting the diaphragm at a peripheral corner of the diaphragm, wherein the structural layer comprises a different material than the diaphragm.

7. The capacitive MEMS die of claim **6**, wherein the diaphragm comprises silicon nitride and the structural layer comprises phosphosilicate glass (PSG) or a borophosphosilicate glass (BPSG).

8. The capacitive MEMS die of claim **6**, wherein the structural layer comprises multiples layers having different glass transition temperatures.

9. A capacitive microelectromechanical systems (MEMS) die, comprising:

a substrate having a through-hole;

a first electrode having a conductive central portion, a peripheral corner, and an annular corrugation;

a structural element disposed in the peripheral corner of the first electrode, the structural element comprising a different material than the first electrode;

a second electrode having a conductive central portion;

the first electrode and the second electrode disposed in spaced-apart relation to form a capacitive structure located over the through-hole of, and supported by, the substrate,

wherein the structural element increases robustness of the capacitive MEMS die relative to MEMS die that does not have the structural element, and

wherein the annular corrugation extends in a direction toward the second electrode and is spaced apart from the substrate, wherein the corrugation increases the compliance of the first electrode.

10. The capacitive MEMS die of claim **9**, wherein the peripheral corner is substantially annular.

11. The capacitive MEMS die of claim **9**, wherein the first electrode comprises silicon nitride and the structural element comprises phosphosilicate glass (PSG) or a borophosphosilicate glass (BPSG).

12. The capacitive MEMS die of claim **9**, wherein the structural element comprises multiples layers having different glass transition temperatures.

13. The capacitive MEMS die of claim **12**, wherein the first electrode comprises silicon nitride and the multiple layers comprise a phosphosilicate glass (PSG) or a borophosphosilicate glass (BPSG) having different phosphorus contents.

14. The capacitive MEMS die of claim **9**, wherein the annular corrugation has softened edges or corners characterized by a radius of curvature greater than 1 μm and less than 50 μm.

15. The capacitive MEMS die of claim **14**, wherein the annular corrugation is located radially outwardly of the through-hole.

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